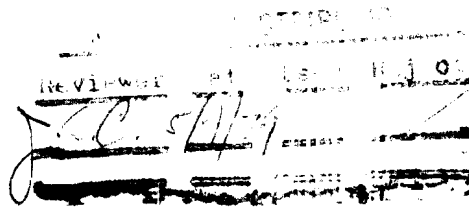CONTRACT REPORT ARBRL-CR-00378

ACOUSTIC EMISSION TESTS OF HF-1 STEEL SHELLS

Prepared by

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August 1978

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)* (mba)
Acoustic emission monitoring has been performed on seventeen hydrostatically loaded, pre-notched and fatigued HF-1 steel shells. A range of notch depths was used. One acoustic transducer was used during each test and its output was video tape recorded and later analyzed in playback while observing the oscilloscope display. The total acoustic emission event per test was found to be proportional to the degree of plasticity exhibited by the shell. No specific AE pattern was found which would predict shell mechanical behavior.
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An insensitivity, mechanically, to induced flaws is implicated by the grouping of yield and failure pressures over the range of notch depths. One test result, from a shell which displayed an unusual amount of ductility, is attributed to either a marked strain rate dependence in HF-1 steel, or to the material in that particular shell being unusual.

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I. INTRODUCTION

This work was conducted as a part of the program on application of NDT methods of quality control in the manufacture of advanced fragmentation steel shell MM&T project #5756654. In order to establish a non-destructive evaluation of the quality of HF-1 steel shells, a program of acoustic emission detection tests has been completed. The first part of the program consisted of acoustically monitoring tensile tests of HF-1 specimens in various heat treatments, with specimen diameters of 1/4, 1/2, and 3/4 inches, and with various notch depths and radii. The second part of the program was to monitor the acoustic emission during hydrostatic loading of pre-notched HF-1 shells. What follows is a report on the second portion of the test program.

The immediate goals of the tensile tests and the hydrostatic shell tests are similar: determine if some characteristics of acoustic emission can be used as a detector of the mechanical response of HF-1 to particular flaw (crack) parameters. This information could then be used to establish objective standards which could be used in the quality control of manufactured HF-1 shells.

II. TEST PROCEDURE AND EQUIPMENT

A. Mechanical Preparation and Equipment

The HF-1 shells were notched on the inner shell wall along the long axis by electric discharge machining. The notch widths were approximately .010" and two notch positions were used, 7-1/2" and 12-1/2" above the base of the shell. To produce fatigue cracks at the notches the shells were cyclically loaded and unloaded, hydrostatically, an unspecified number of cycles prior to the final test. Although cycling in this manner usually produces fatigue cracks, no tests were carried out to verify that fatigue cracks had been produced by this procedure.

The bottom of each shell was machined and sanded smooth to provide a surface acceptable for mounting a transducer.

One axial (long axis) strain gage and one transverse strain gage were mounted on each shell at the same height as the notch and 120° away from the notch. Both gages were on the outside surface of the shell. During each test axial versus transverse strain was plotted on an X-Y recorder.

A pressure transducer was inserted in the hydraulic line just before the shell was used to monitor shell internal pressure. An X-Y recorder plot of internal pressure versus transverse strain was made for each test.

The shells were hydrostatically loaded by pumping with oil to Provide internal pressure. Before pumping each shell was filled with oil and bled of air. During each test the pumping rate was controlled manually.

B. Acoustic Emission Equipment

The AE System consisted of an acoustic transducer, oscilloscope with amplifying plug-in, and a video tape recorder to record the analog acoustic emission signals.

In the first test a Tektronix 502A oscilloscope and a Hewlett-Packard 461A amplifier were used. In all other tests the oscilloscope mainframe used was a Tektronix 551 dual beam model. Test #2 thru 8 were recorded using a Tektronix type O operational amplifier plug-in. The highest gain setting was used and signals less than 1kHz were rejected. Tests #9 thru 18 utilized a Tektronix type 1A7A high gain differential amplifier plug-in. Input settings of .5 and .2 mV/cm were used and the bandpass filters were set at 1kHz and 1MHz. This unit provides approximately .25 volt per centimeter of screen deflection as an output to the video tape recorder.

A Panasonic model NV 3020 video tape recorder with 1/2" video tape (Sony V-32) was used in all tests. Coaxial cable was used throughout for signal transmission.

The transducers used were Panametrics model V105. The transducer diameter is 3/4". These transducers possess a generally flat response from 200Hz to 2MHz. The bandwidth of the tape recorder extends from 0 to 3MHz.

C. Acoustic Emission Procedure

The transducer was attached to the shell base directly below the notch. It was held in place by wedging it between the shell base and the floor. In tests #1 thru 8 wood blocks and foam rubber were used as spacers, while a spring loaded arrangement was used in the remainder of tests. Silicone stop cock grease was used as the couplant.

Tape recording began at 1000 psi shell pressure for tests #1 thru 8. After it was noted that significant AE signals occurred at this low pressure the procedure was altered so that recording began before any pumping in the rest of the tests. The time, to the nearest second, at increments of 1000 psi shell pressure was recorded so as to correlate the video tape record with the pressure-strain record.

The condition of the transducer was checked between tests. Visually, the wearplate was inspected for cracks. Functionally, the transducer was checked by providing an input which was fairly reproducible and noting the amplitude of output displayed on the oscilloscope. The input was provided by a piezo-electric sparker which caused an electric discharge to travel a fixed distance to a steel block which had the transducer attached. Prior to the beginning of pressurization in most tests the transducer to shell contact was verified by tapping the hydraulic piping at the pump and noting the transducer output.

During the course of the tests, transducers #1 and 2 were removed from service when damage to the wearplates occurred.

III. ACOUSTIC EMISSION DATA ANALYSIS

The AE data are converted from analog signals to single events versus time. This is achieved by observing the video tape playback on an oscilloscope and placing a mark (pip) on an X-Y recorder set up as a strip chart recorder each time a single acoustic event is detected visually. Amplitude discrimination is made possible by having two different amplitude pips to handle "small" and "large" amplitude acoustic events. "A single acoustic event" is meant to describe the entire wave-train directly following the initiation of some resolvable transducer voltage output. This is contrary to the usual meaning of AE counts, which is the sum of the number of times the transducer output crosses through some arbitrary voltage threshold. For our purposes a single acoustic event could be read as numerous (10 - 1000) "counts" in the conventional sense.

A shell pressure versus time plot is made for each test and the AE events are transcribed from the strip chart to the horizontal time axis as vertical line segments. Two heights of lines are made so as to reflect the amplitudes of the signals.

The above described technique for transcribing the AE information has a significant strongpoint as well as an important limitation. It is quite easy for the trained eye to reject and not include spurious re-corded signals as acoustic emission. Specifically, the familiar ringdown of the AE signal is used as a trademark of a bonafide AE signal. Very low frequency signals (pumping noise) and high frequency, large amplitude "noise" spikes are easily rejected. The ability to record AE events rather than voltage excursions is quite powerful, and logically seems to be the better choice. The large number of counts experienced in con-ventional counting is largely a transducer phenomenon (ringdown) and once the real time AE information is recorded in this manner, the AE single events cannot be retrieved. The disadvantages of the technique involve the qualitative nature of human judgement and the limits of high speed event resolution. A reasonable estimate of the fastest event rate re-solvable with this technique is 2 - 3 events per second. This event rate is often exceeded in HF-1 testing, generally in segments just be-fore failure.

IV. RESULTS

The AE data are presented as events in pressure versus time plots in Figures 1 through 35. As previously described, each vertical line above the time axis represents an acoustic event. The amplitude of the observed signal is reflected in the height of the line. Also included

for each test is a graph of axial strain versus transverse strain combined with a plot of pressure versus transverse strain. Table I compiles various quantifiable aspects of the individual tests as well as information derived from the AE and mechanical plots.

In the table, the existence of a fatigue crack and its depth is judged visually from the shell's broken surfaces following the completed test. The pressure at which a change in slope in the pressure versus transverse strain and in the axial versus transverse strain curve is designated the yield point. The yield point from the latter curve is the value utilized in the discussion section. Tests #8, #15, #16, and #17 have multiple pressure cycles. Test #8 was cycled five times just below yield as a planned mechanical program. The time to failure indicated is from the last cycle only. The other tests were pressurized more than once because of 0-ring or hydraulic line leaks. A value for total AE events is generated by using the sum of the events from all the cycles minus those portions previously experienced in the pressure history of the shell.

V. DISCUSSION OF RESULTS

Increased acoustic activity may be found in three specific regions of each test. These are: just prior to failure; in the vicinity of yield; and soon after pumping begins, during elastic loading. Not all tests exhibit increased activity in each region.

All but three tests (#2, #16, and #17) have some level of acoustic activity just before failure, as seen in the plots of AE events versus pressure. Each test having a yield point has at least one AE count which can be ascribed to yielding. But, in most cases, the acoustic activity is not distinctive enough so as to be able to predict yield from just this information. Most tests have some AE early, soon after loading begins, and some have quite pronounced acoustic emission event rates (#7, #11, #12, #13, #14, #16, and #18). This phenomenon seems to defy any attempts to correlate it with any striking mechanical parameter, and could be due simply to the seating of thread surfaces or similar contact.

An interesting result is a correspondence between the number of acoustic emission events and the magnitude of change in strain following the yield point. Figure 36 is a plot of AE events after yield versus change in strain after yield. The strain value is an arithmetic sum of axial and transverse strain variation (microstrain) after yield. Therefore, this value represents an absolute change in strain and may be considered a measure of the plasticity experienced by the shell. The figure clearly demonstrates the proportionality of AE events to change in strain for both low notch and high notch tests. Test #7 presents an exception to this relationship for the low notch tests. In this case the number of AE events after yield is abnormally small for such a large

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TABLE I. ACOUSTIC EMISSION AND MECHANICAL DATA

TEST NO.	NOTCH LOCATION	SHELL DESIGNATION	FATIGUE CRACK?	CRACK AND/OR NOTCH DEPTH (IN)	PRESSURE @ SLOPE CHANGE (PRESSURE VS TRANS ϵ) (KSI)	PRESSURE @ SLOPE CHANGE (AXIAL ϵ VS TRANS ϵ) (KSI)	FAILURE PRESSURE (KSI)	TRANSVERSE STRAIN > YIELD ($\mu\epsilon$)
1	low	.264B	no	.233	none	none	14.6	--
2	low	.210C	no	.176	none	none	16.2	--
3	low	.210B	no	.198	none	14.6	15.8	100
4	low	.150B	yes	.390	none	none	9.2	--
5	low	.180C	yes	.259	none	14.8	16.6	150
6	low	.072A	yes	.093	none	14.6	17.9	235
7	low	.072B	?	?	16.6	14.7	--	335
8	low	.210A	yes	.280	16.2	16.2	18.3	350
9	high	.180A	yes	.376	none	none	8.4	--
10	high	.090C	yes	.138	14.8	14.4	17.2	1625
11	high	.090A	yes	.103	none	none	15.0	--
12	high	.090B	yes	.109	14.4	13.3	16.7	400
13	high	.065A	?	?	15.7	15.2	--	170
14	high	.065B	?	?	15.4	15.0	15.8	100
15	high	.065C	?	?	14.9	14.7	16.2	270
16	high	.049A	?	?	none	none	13.9	--
17	high	.049B	?	?	none	14.3	14.9	75
18	high	.049C	?	?	none	none	15.0	--

TABLE I. ACOUSTIC EMISSION AND MECHANICAL DATA (Continued)

AXIAL STRAIN > YIELD (με)	TIME TO FAILURE (sec)	PRESSURE @ 1000 TRANS με (ksi)	PRESSURE CYCLES	NOTES	TOTAL AE EVENTS	TRANS-DUCER NO.	AMPLIFIER	TEST NO.
--	154	14.7	1		3	1	HP 461A	1
--	194	15.0	1		3	1	Tek 0	2
25	189	14.3	1		8	1	Tek 0	3
--	?	14.3*	1	*extrapolated value	--	--	Tek 0	4
15	181	14.8	1		6	1	Tek 0	5
20	207	14.3	1		19	2	Tek 0	6
285	--	14.5	1	did not fail	32	2	Tek 0	7
330	241	13.1	5	counts & time, last cycle	4/9/8/8/42	2	Tek 0	8
--	162	10.5	1		11	2	1A7A	9
130	408	10.5	1		550	2	1A7A	10
--	207	11.0	1		103	2	1A7A	11
65	187	10.7	1		119	2	1A7A	12
0	--	10.9	1	did not fail	88	2	1A7A	13
15	188	10.7	2	did not fail at notch	111/29	2	1A7A	14
40	184	11.3	2	did not fail at notch	3/9	2	1A7A	15
--	162	10.7	3	did not fail at notch	12/4/4	3	1A7A	16
5	211	10.7	1	did not fail at notch	11	3	1A7A	17
--	159	10.7	1	did not fail at notch	25	3	1A7A	18

change of strain value, and test #15 deviates from the general pattern formed by the high notch tests. This test also has a smaller than normal AE count, which could possibly be explained by a bad transducer. The transducer had to be replaced following test #15 and degradation in performance prior to the test is a possibility, although not indicated at the time.

Note that in Figure 36 the low notch data set shows fewer AE events than the high notch tests for the corresponding values of change in strain. Or, in a different way, the slope of the low notch tests is higher than that of the high notch tests. This is explained by the increased sensitivity of the AE electronic system employed in the high notch tests. Just the change in location of the notch may also contribute to this effect.

When the total AE events are plotted against change in strain after yield, Figure 37 results. A relationship just as in Figure 36 is seen. The low notch tests are grouped perhaps better than in the previous graph. The high notch tests arrange themselves very similar to the previous plot, but besides test #15 being out of place, test #11 appears to deviate from the crude linear relationship. There seems to be no explanation for the large number of AE counts ascribed to this test. The fact that total AE events still follow porportionally to change in strain after yield means that these AE event trends are reflected in acoustic activity before and after yield.

The mechanical behavior of the shells, as seen in Figure 38 as a plot of yield and failure pressures versus crack depth, follows a reasonable relationship. The failure pressure generally decreases with increasing notch plus crack depth. This is particularly true of the low notch tests. Exceptions within this test set are tests #5 and #8. It should be noted that these two shells had cracks within the .250" - .300" depth range and their larger failure pressures might be significant. This could imply a mechanical insensitivity to such a depth flaw, due to inhomogeneous shell wall microstructure, etc. In the high notch tests only four of ten shells failed at the notch, tests #9, #10, #11, and #12. As in the acoustic emission comparison, test #11 represents somewhat of an exception. Its failure pressure is rather low compared to that of shell #12, which had a deeper notch. The data from the six remaining high notch tests are also shown, but it should be emphasized that none of these shells failed at the notch.

A survey of the yield pressure information presented in Figure 38 seems to imply that the yield pressures tend to be almost the same, regardless of the failure pressure. Most interesting is the fact that this yield pressure value is approximately the failure pressure of the shells that experienced no yield point. (Tests #4 and #9, with very deep cracks not included.) First, this implies that the yield point phenomena is insensitive to local stress concentrations; and second, this implies that those shells which fail without a yield point cannot, for

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some reason, survive the instability associated with yielding.

Also included as part of the information in Figure 38 are the total AE events for each test. An inspection of this value for the low notch reveals that the number of counts is roughly proportional to the difference in pressure from yield to failure.

A very notable exception to the normal range of acoustic emission activity is found in test #10. Very high count rate AE begins at about 7000 psi and continues until yield, where practically no AE occurs. Then approximately 30 seconds before failure AE begins again at a very rapid rate, with very large amplitude signals. The unusual feature is the extremely large number of AE events. Mechanically, the axial versus transverse strain plot shows an unusually large amount of plastic deformation occurring. At this point the reason for the large degree of plastic flow is not apparent. It does appear, however, that the pumping rate for this test was slightly slower than the others, as evidenced by the slope of the pressure-time curve. If this material is indeed strain rate dependent to this degree, unusual material behavior might easily be expected. From this observation, a slightly higher strain rate than normal might be expected to cause the material to become quite brittle. Because of the complexities in strain fields caused by notches it is even conceivable that the notch sensitivity discussed above might be due more to the differences in local strain rates induced by varying notch depths. If, however, the behavior of this shell is due to an unusual condition of the shell material, independent of strain rate, then the acoustic emission did quite strongly indicate this unusual material.

Test #13 was halted when the 0-ring sealing the hydraulic line to the test shell via a threaded cap suddenly popped out beneath the cap and released the internal pressure. An attempt was made to compare the signals from this test to those from other tests to determine if a difference in waveform could be noticed. A sampling of signals from tests #10 and #13 provided no obvious variation in waveform between the two. It should be added that there is no positive information which would indicate the 0-ring as the course of AE in test #13.

Waveform analysis of tests #10 and #13 also suggest that there is no change in frequency of AE signals as the test progresses. This judgement is hindered by the fact that very large amplitude signals, usually found just prior to failure, are normally quite distorted by the video tape recorder.

VI. CONCLUSIONS

1. The frequency of acoustic emission events is proportional to the extent of plasticity exhibited by HF-1 steel shells.

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2. The above implies that as HF-1 becomes more brittle, fewer AE events would be expected. Therefore, the amount of useful information diminishes. If, however, a large degree of plasticity (as found in test #10) is the behavior of interest, then AE may well provide an early indication of it.

3. For the majority of shells tested there is no clear pattern of AE events which will distinguish the various mechanical behavior patterns; yield, no yield, early failure, high failure pressure, etc.

4. It appears that HF-1 steel shells are somewhat insensitive to induced flaws. Test shell yield pressure, or shell failure pressure if no yield occurred, is confined to a rather narrow band of pressure values, regardless of notch conditions. Additionally, 5 of 18 shells tested did not even fail at the notches (and at least one of these shells had a fatigue crack). Both of these observations support the view that inherent material properties control the mechanical behavior.

5. A marked sensitivity to strain rate may be inferred from the unusual behavior of one test (#10). Decreasing ductility with increasing strain rate is indicated.

Some acoustic emission parameters reflect the behavior of pre-notched HF-1 steel shells. It would appear that the AE information diminishes, and therefore loses its usefulness, as shell ductility diminishes. Therefore, existing critical cracks may not be easily detected with acoustic emission. It does seem that the characteristics of the material as tested may have overshadowed the effects of the induced flaws.

The analysis of these results is hindered by a lack of information as to what characteristics of HF-1 steel are expected to be the sources of an unsuitably manufactured product. Insensitivity to some induced flaws implies more serious flaws inherent in the tested material. The possibility of an extreme strain rate effect might be logical under these conditions.

It would seem natural to apply acoustic emission testing techniques to as manufactured material, with no induced flaws. Variations in AE correlated with the ultimate strengths of shells loaded in stress configurations of interest seems to be the only way to develop an evaluation technique which can be applied to the purpose.
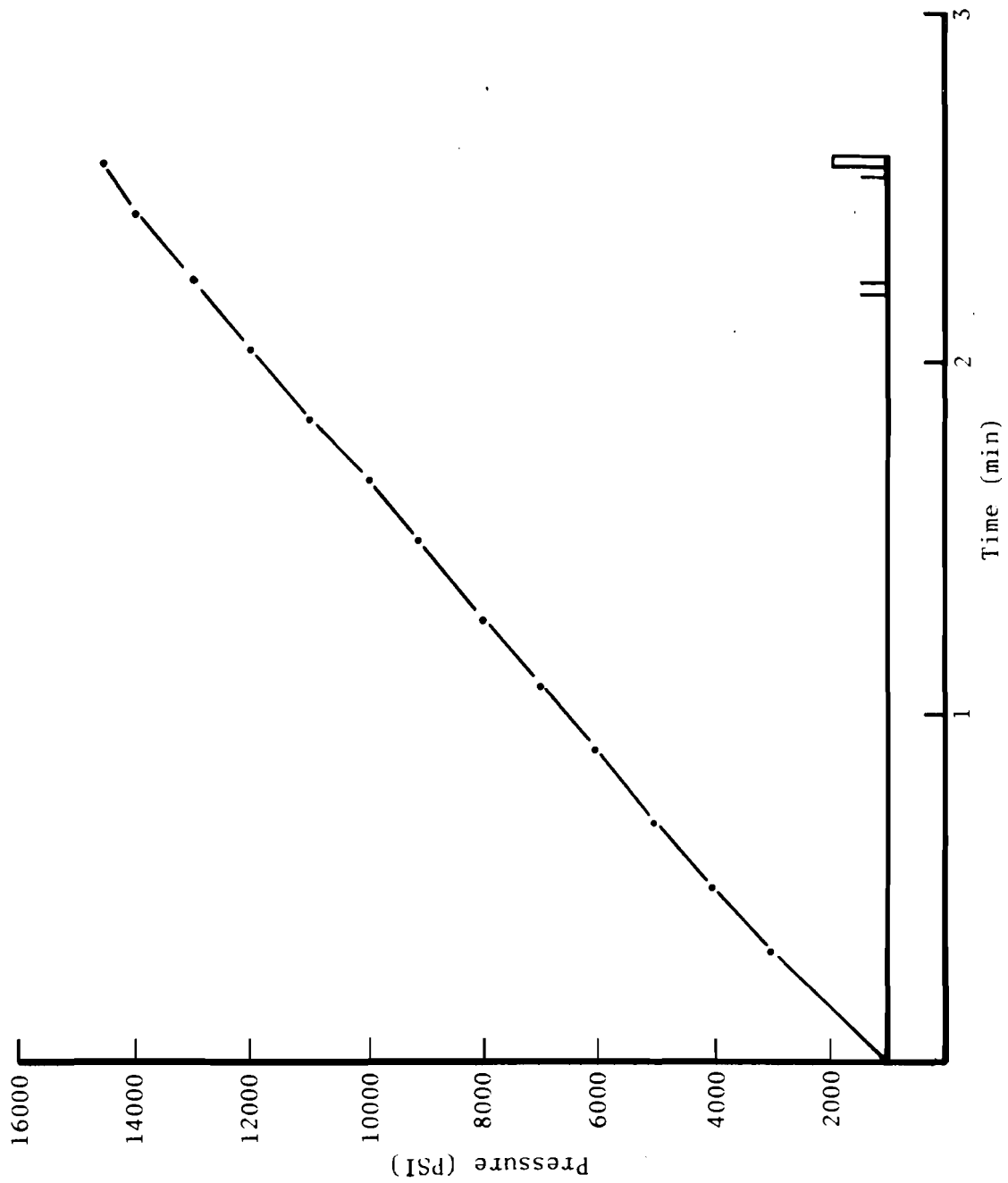
Figure 1. Test #1 Shell Pressure versus Time with Acoustic Emission Events (low notch, no fatigue crack)
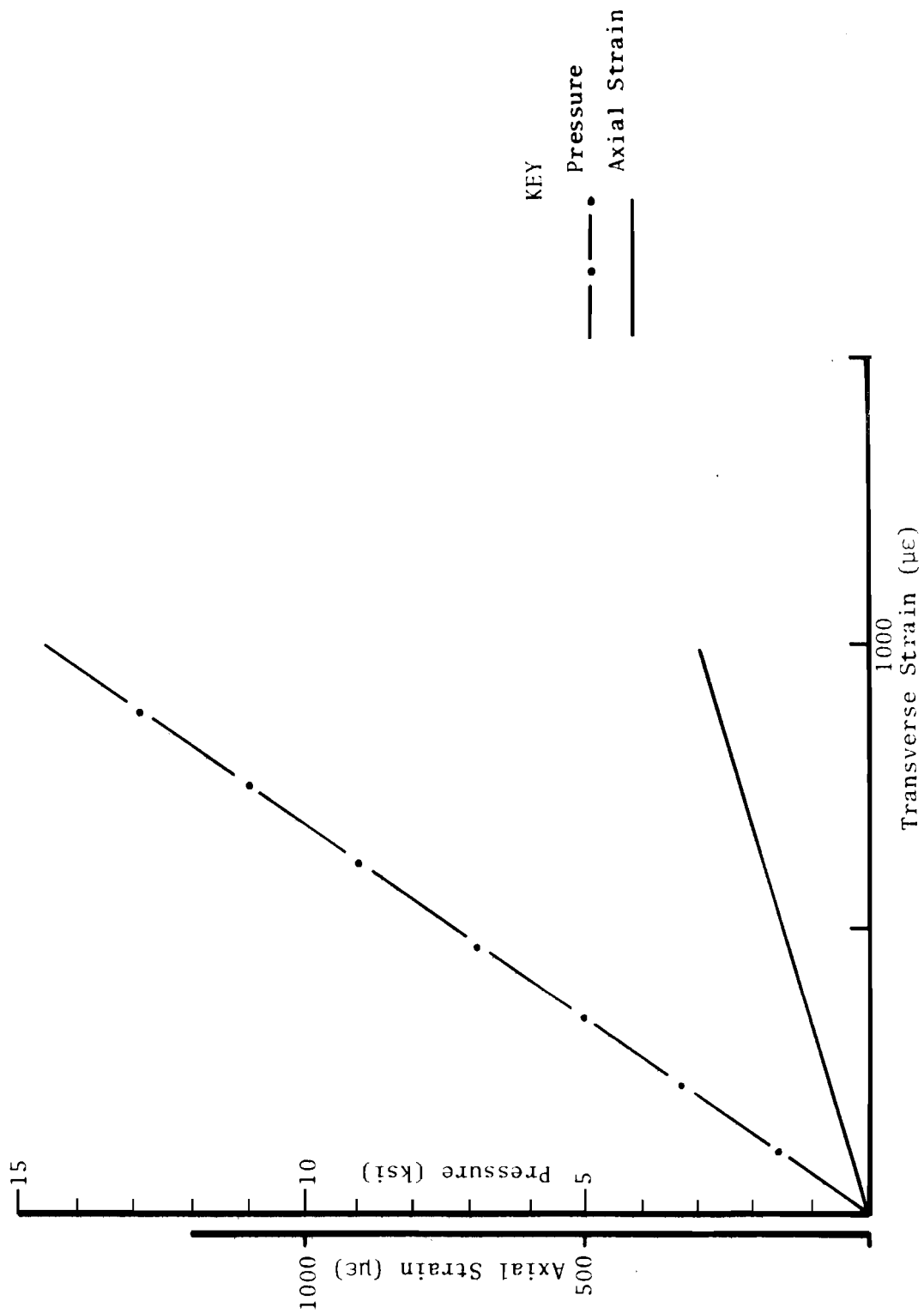
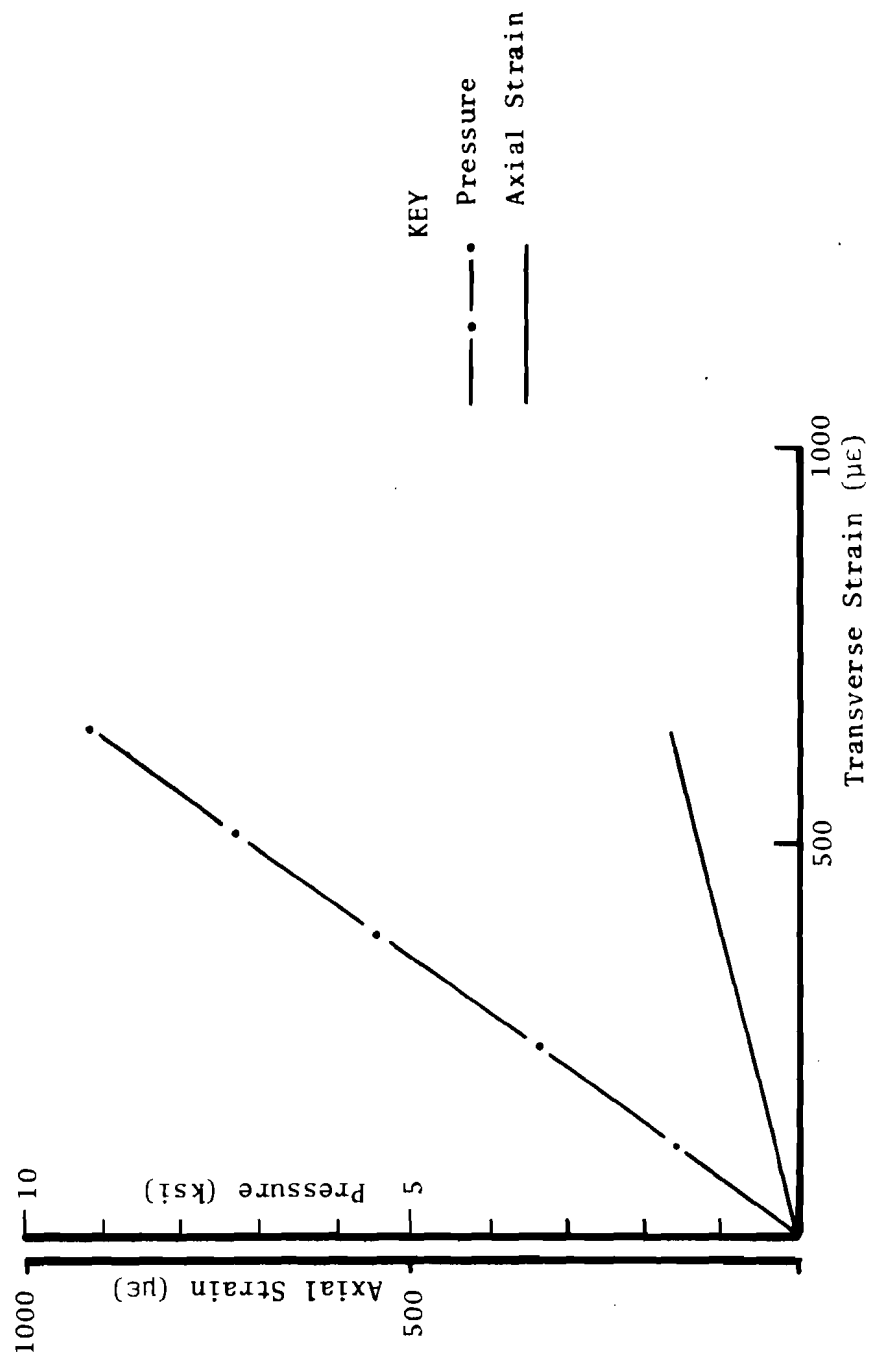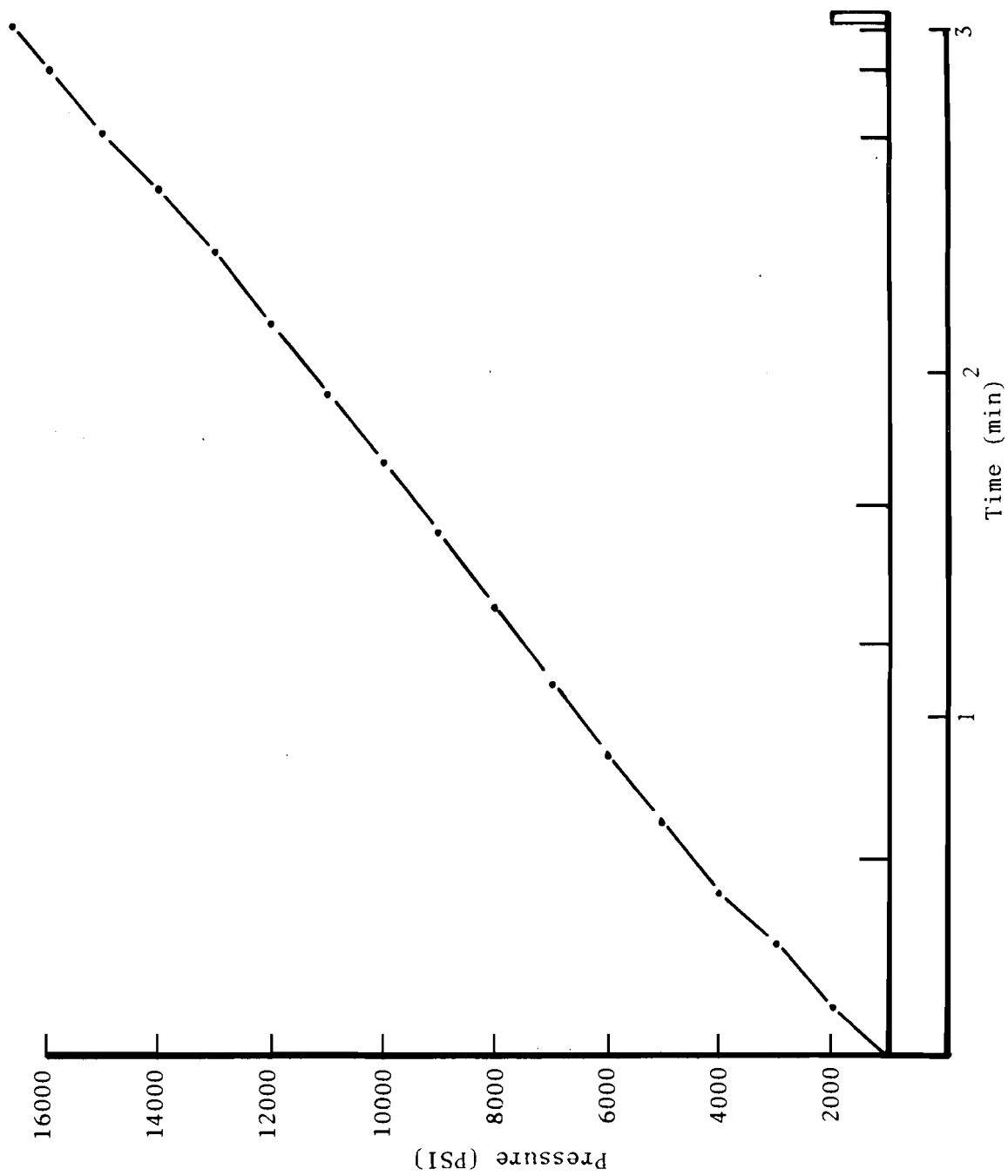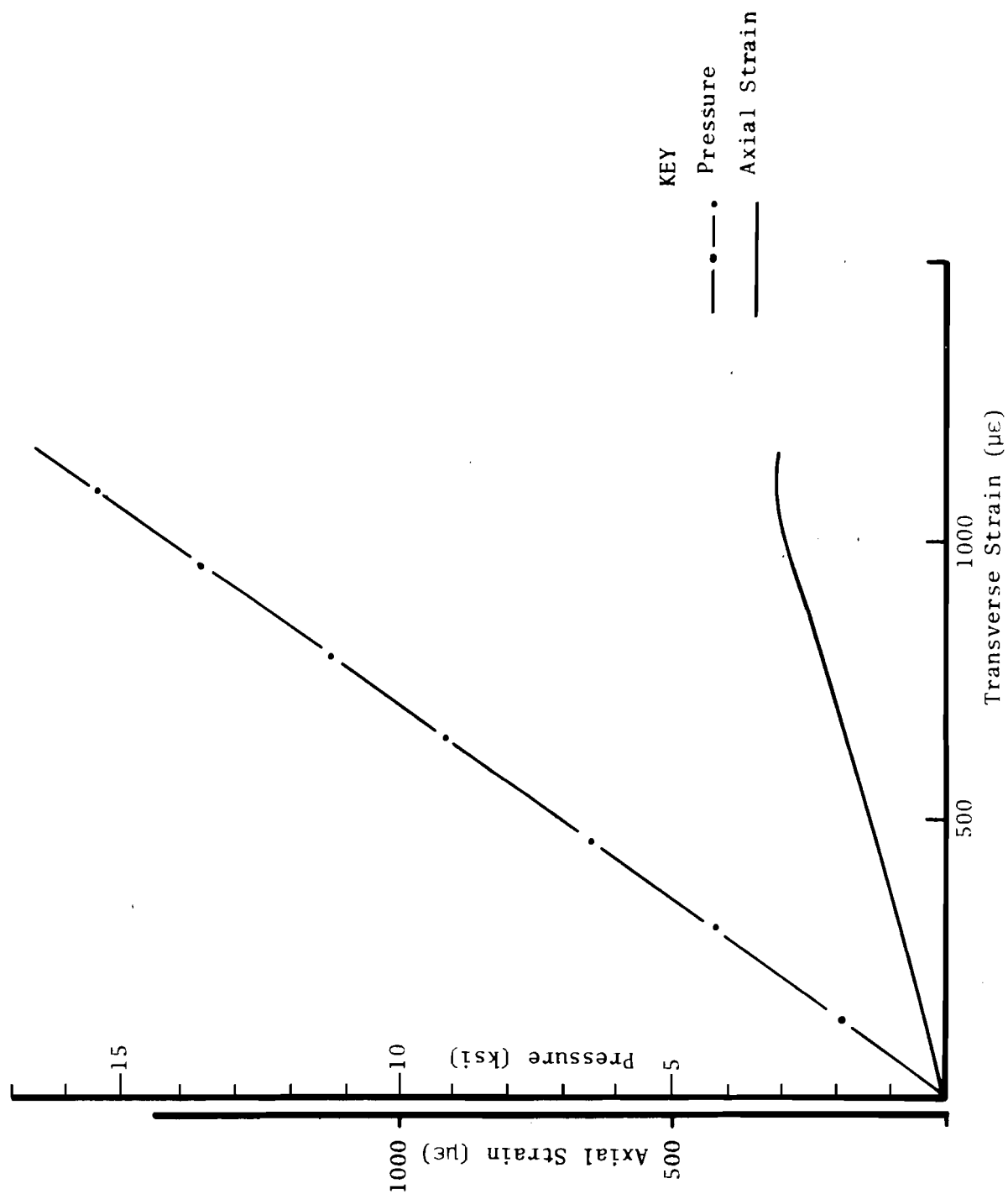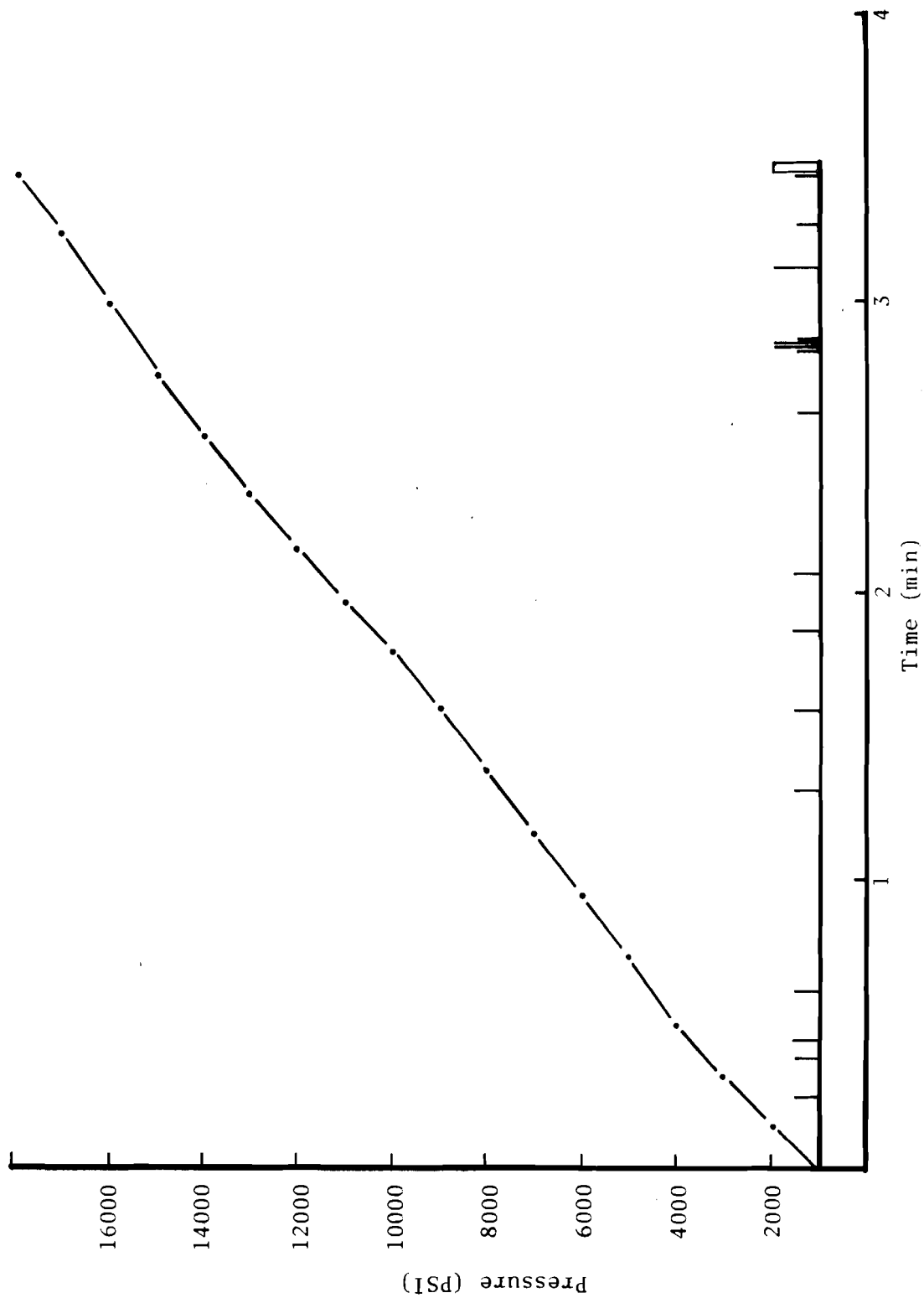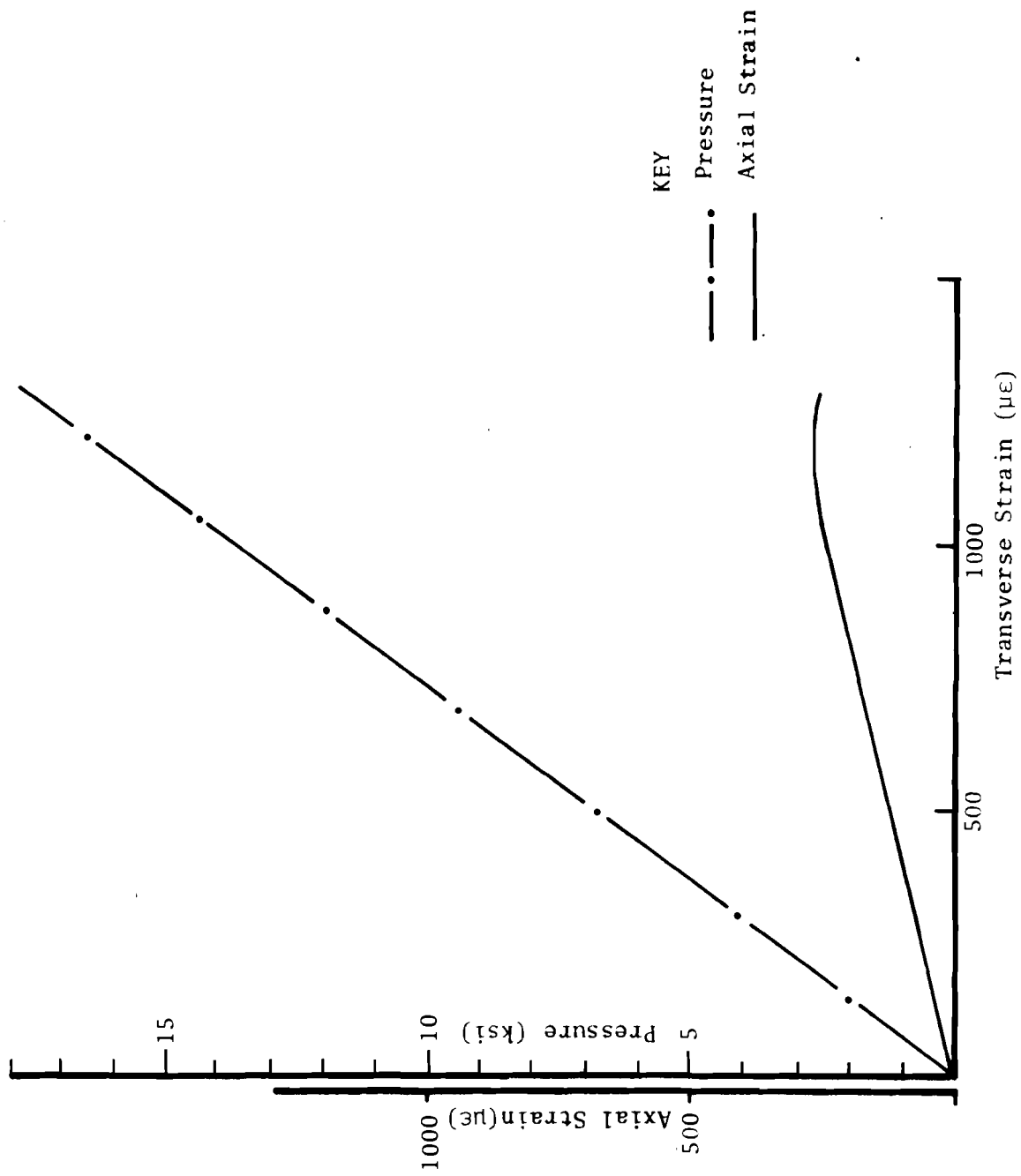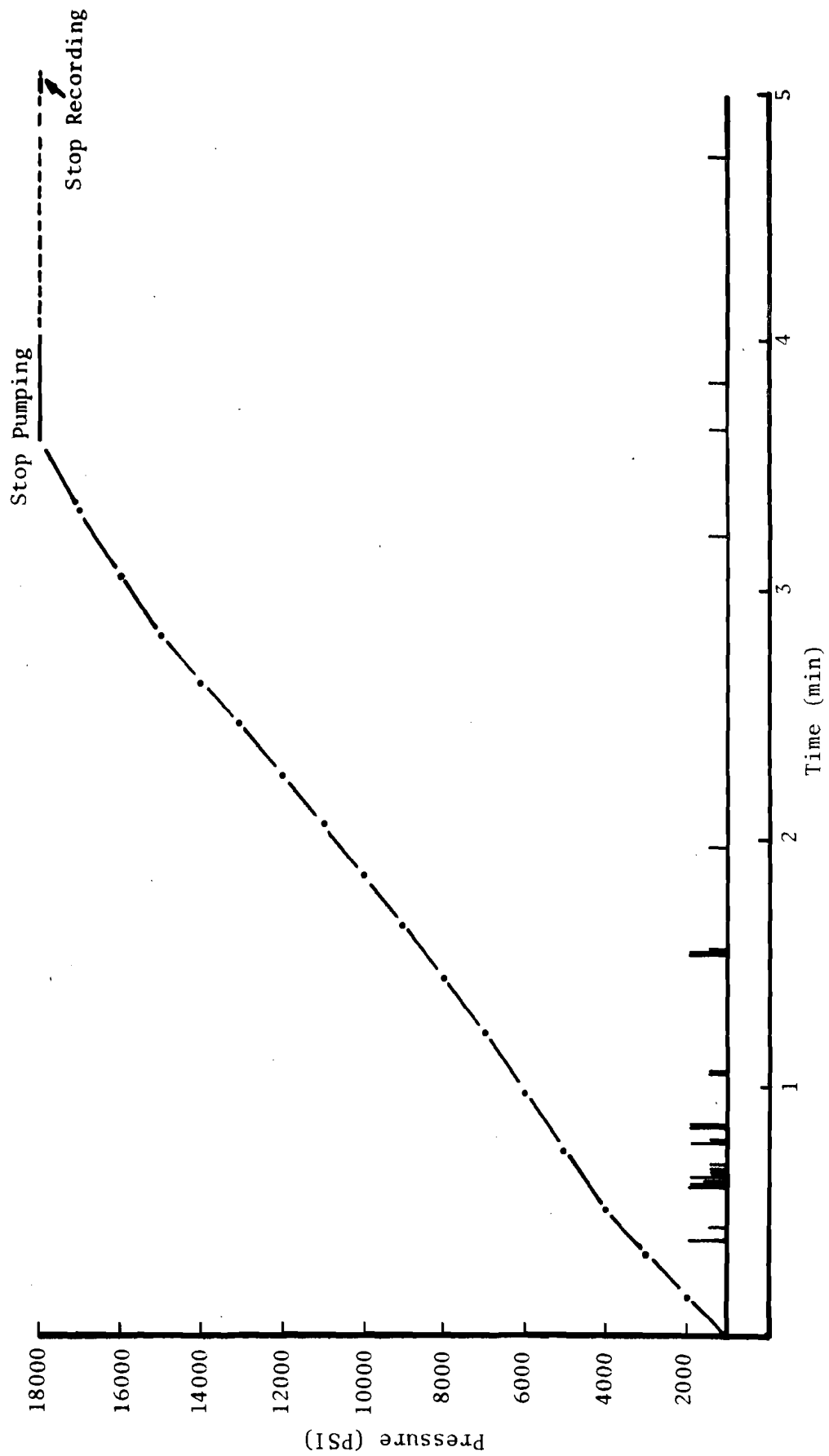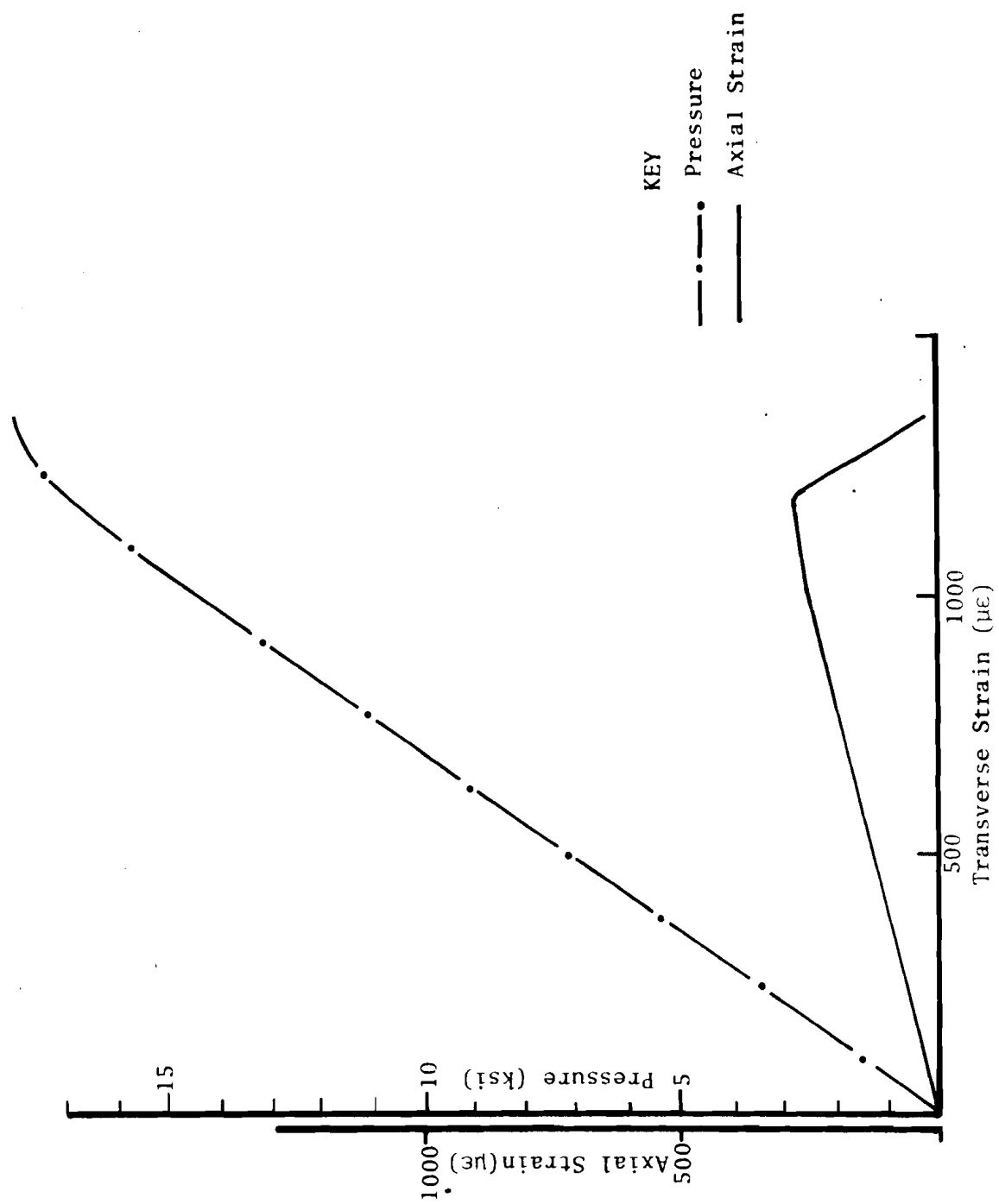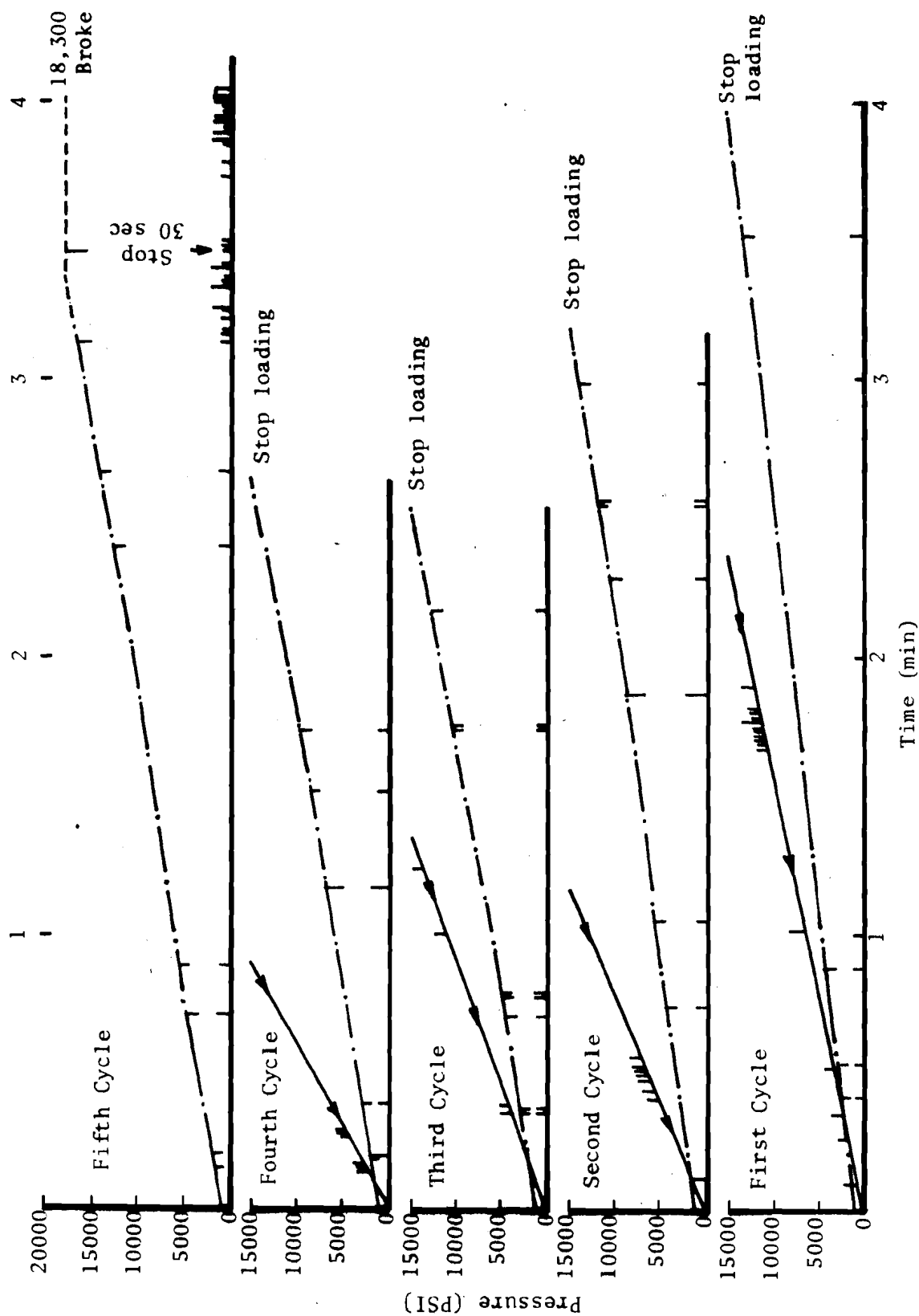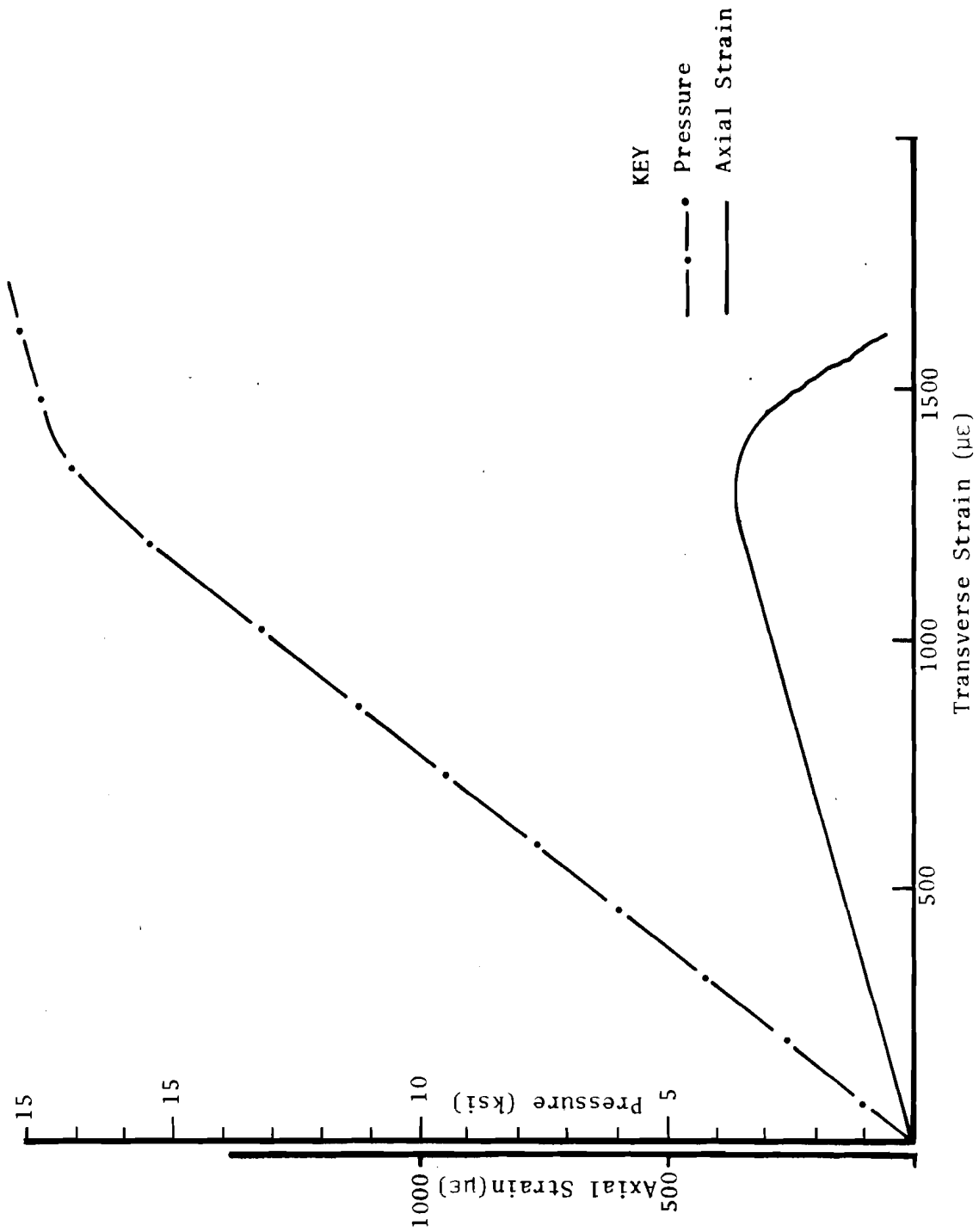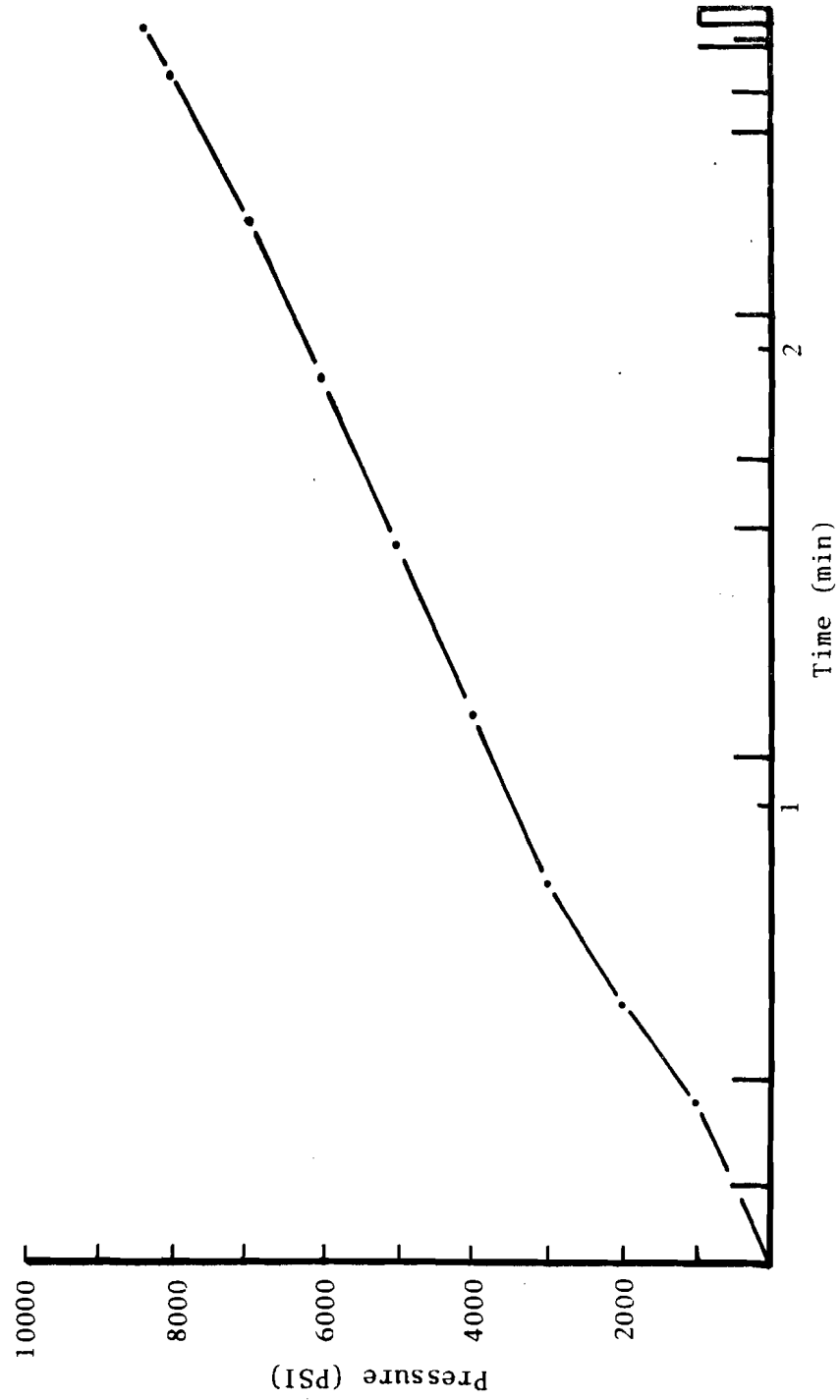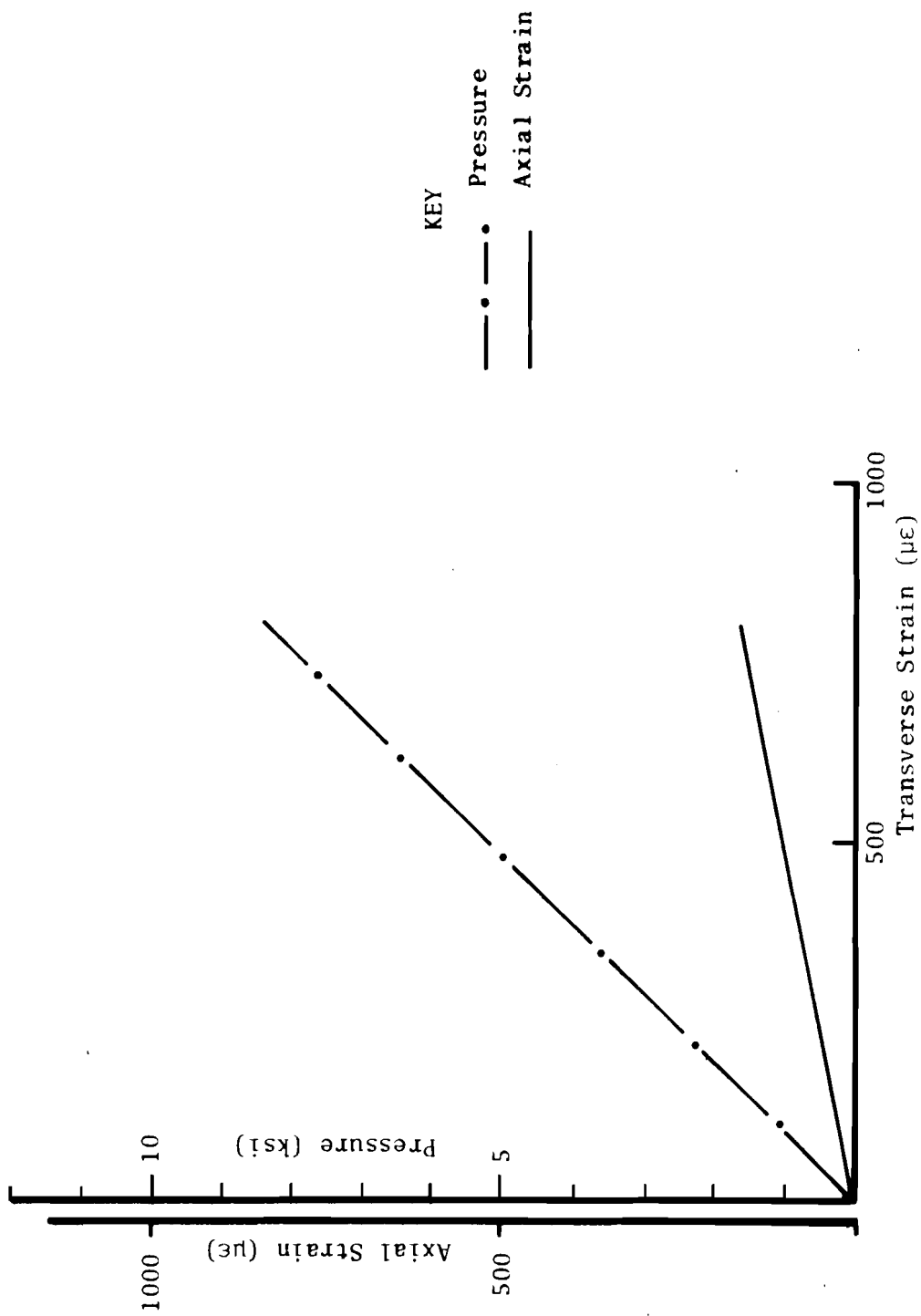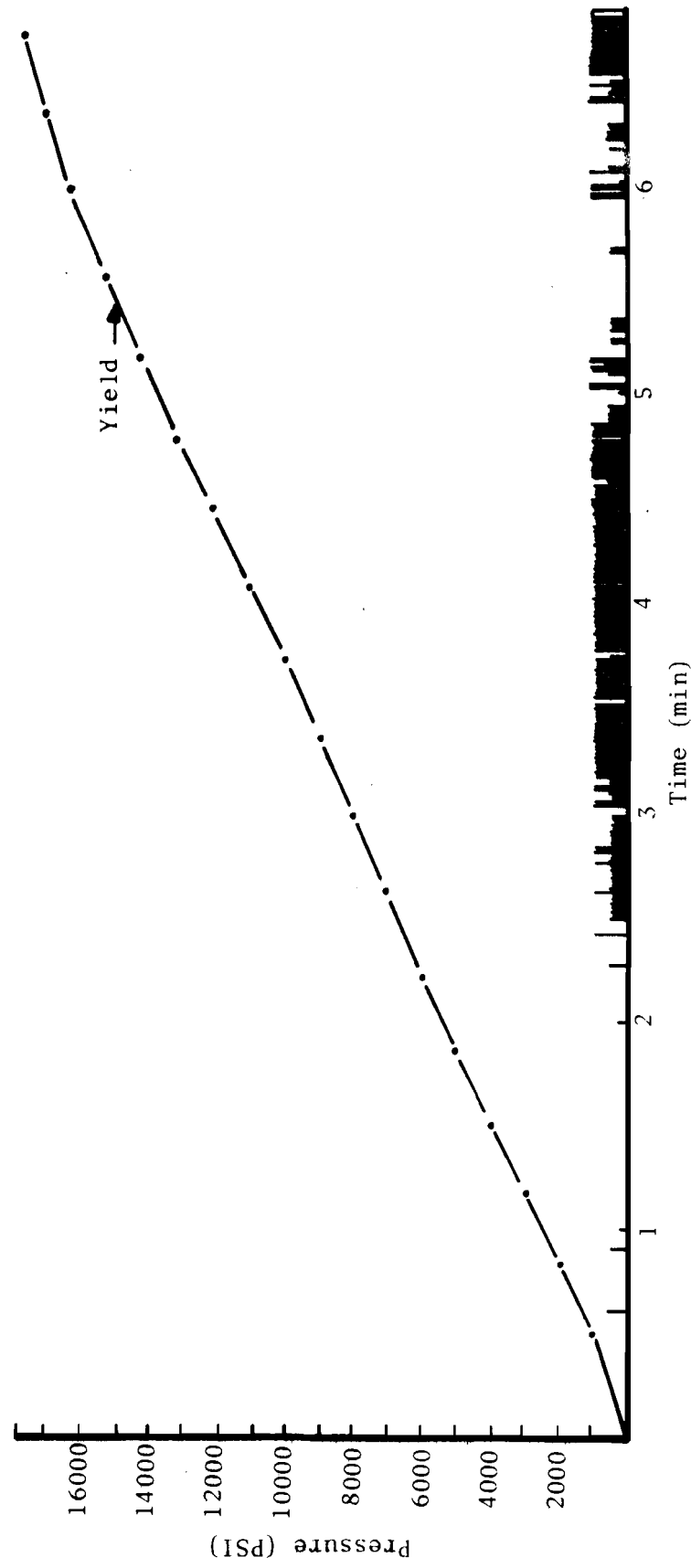Figure 2. Test #1 Shell Pressure and Axial Strain versus Transverse Strain
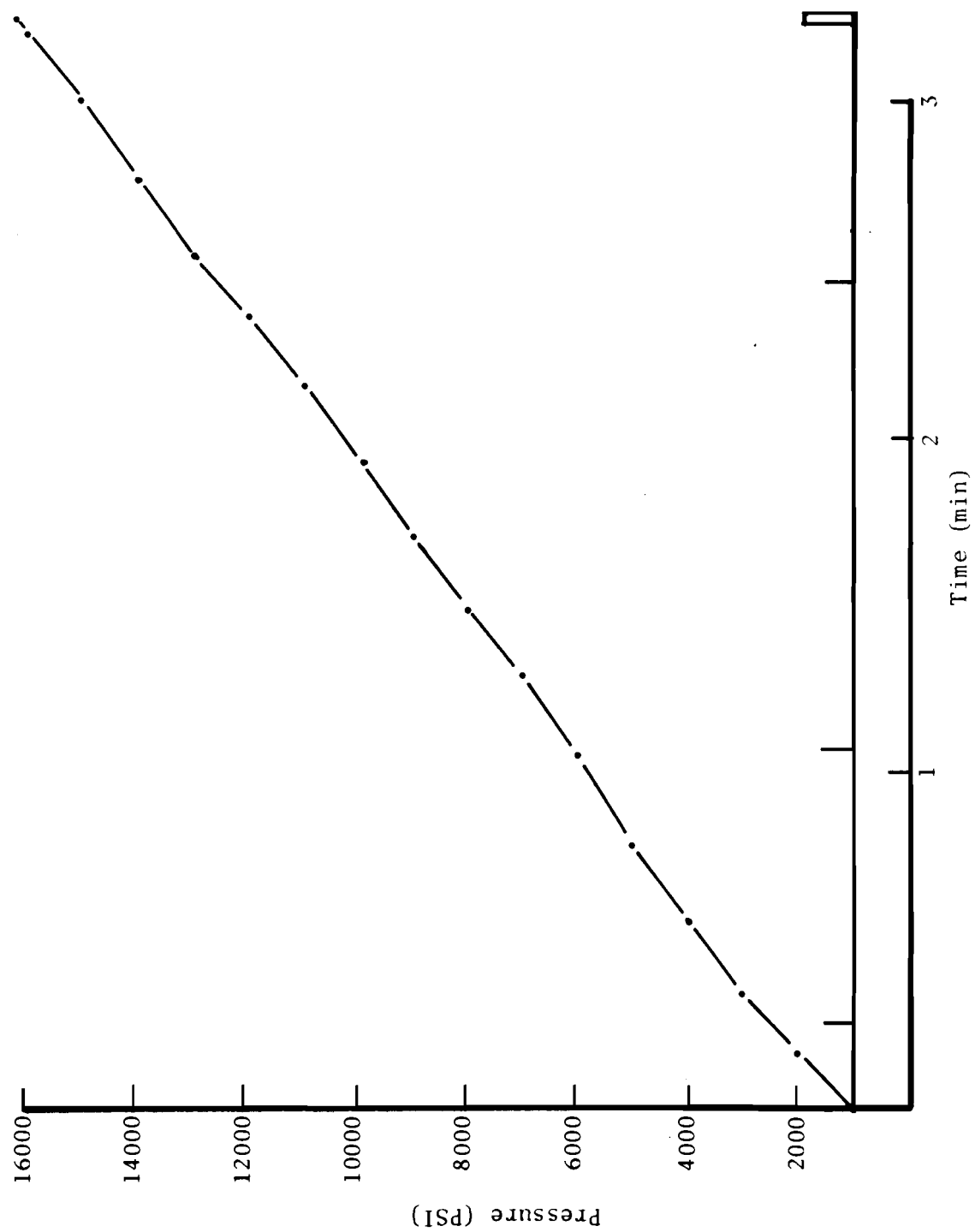
Figure 3. Test #2 Shell Pressure versus Time with Acoustic Emission Events (low notch, no fatigue crack)
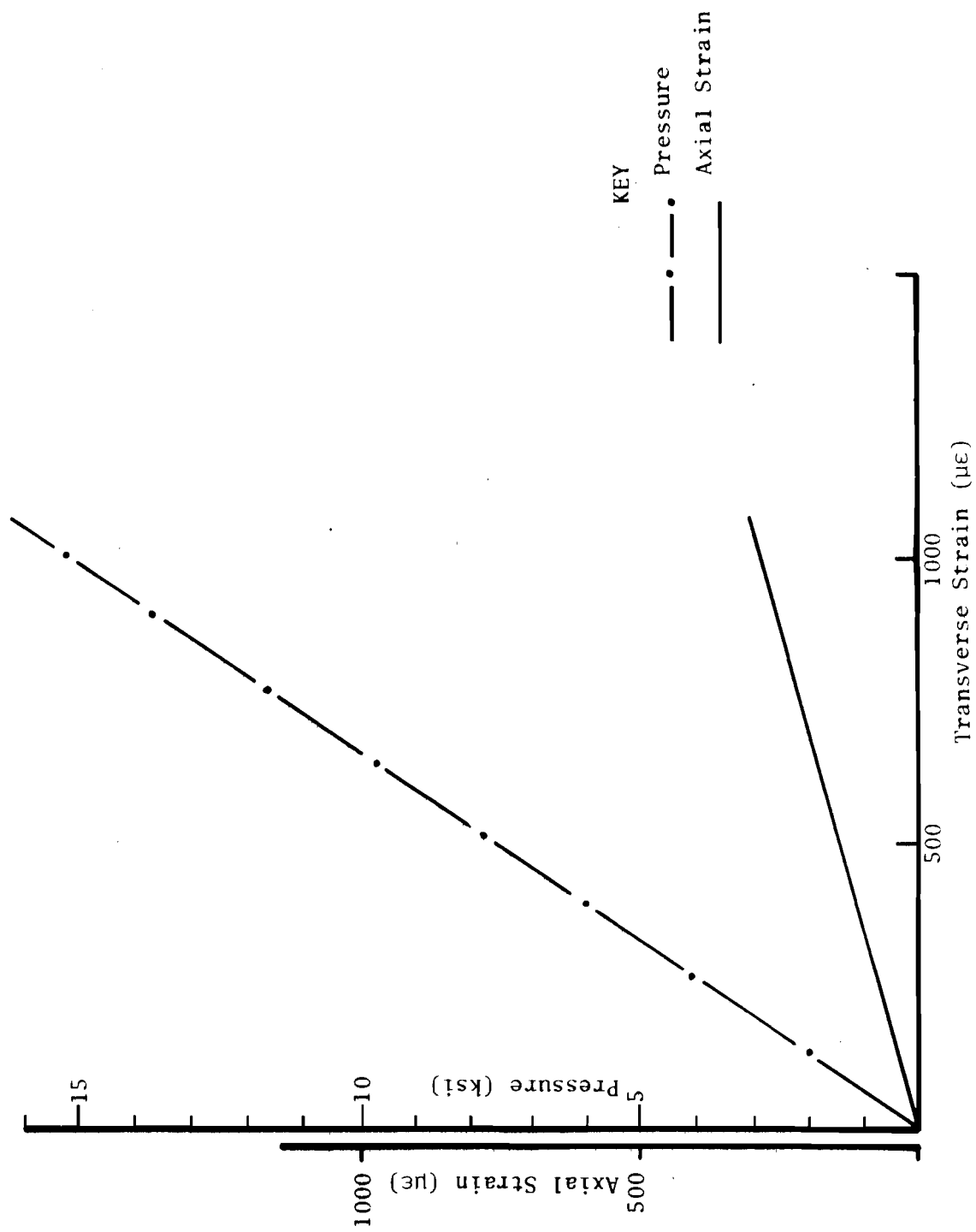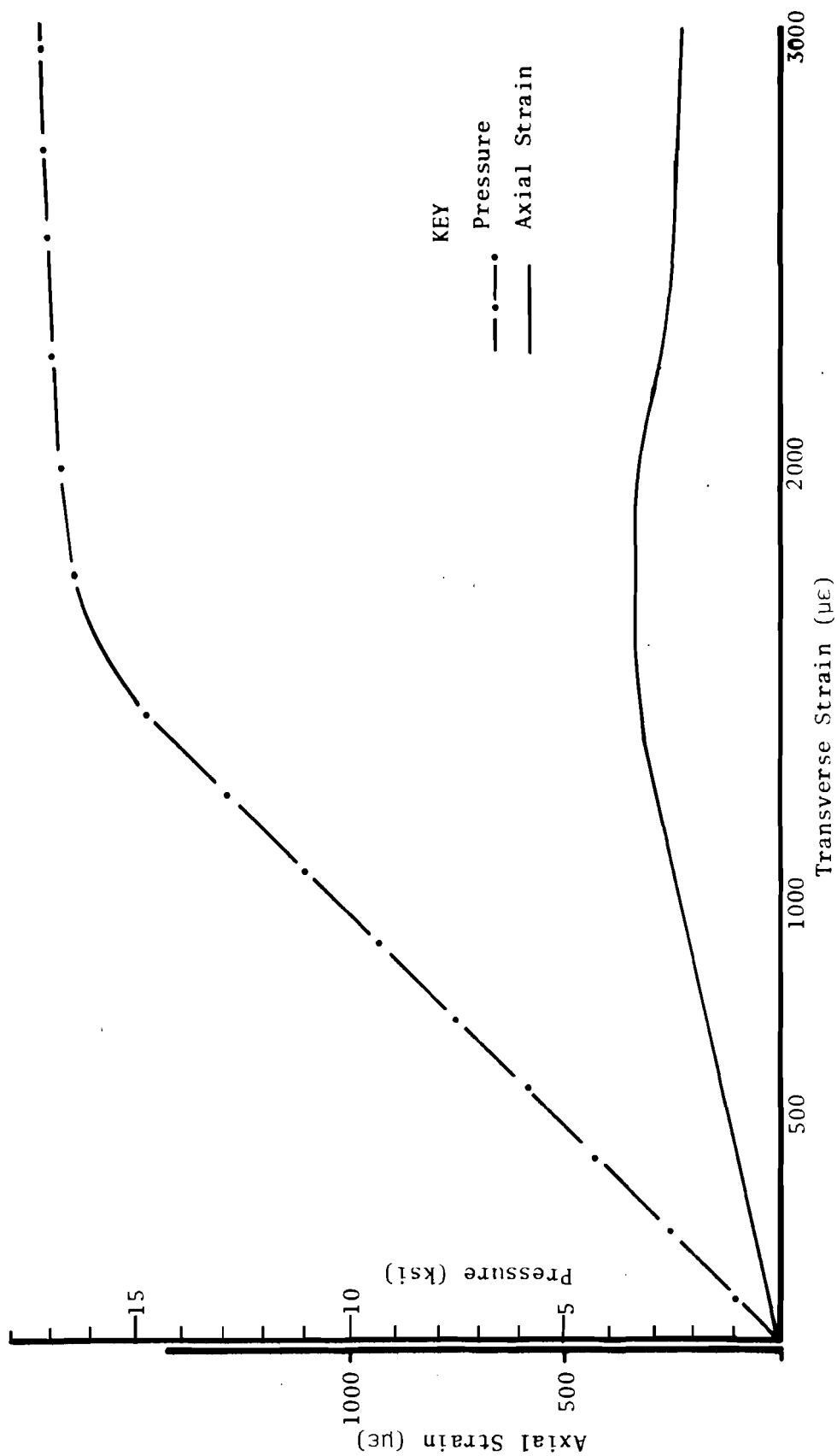
Figure 4. Test #2 Shell Pressure and Axial Strain versus Transverse Strain

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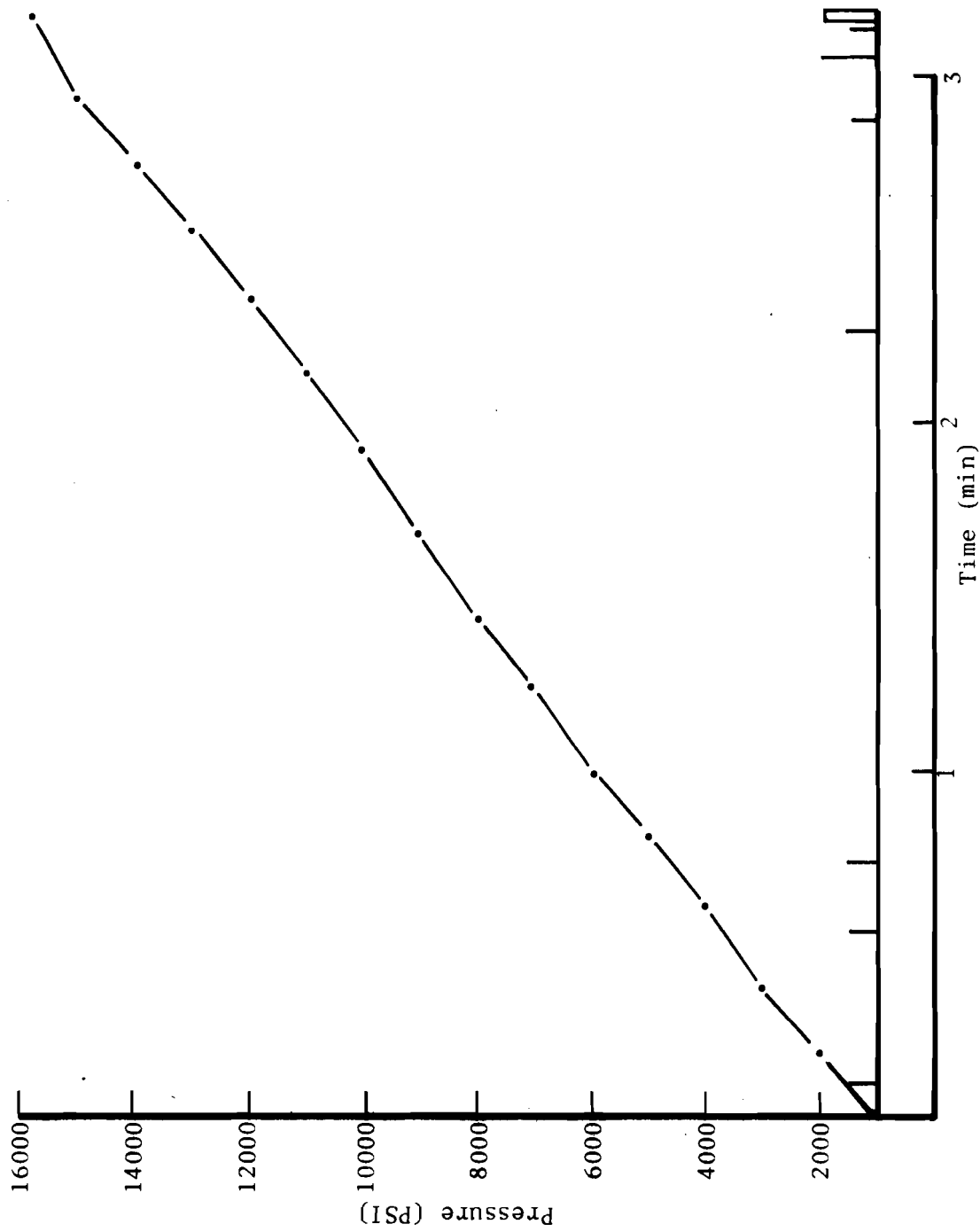
Figure 5. Test #3 Shell Pressure versus Time with Acoustic Emission Events (low notch, no fatigue crack)

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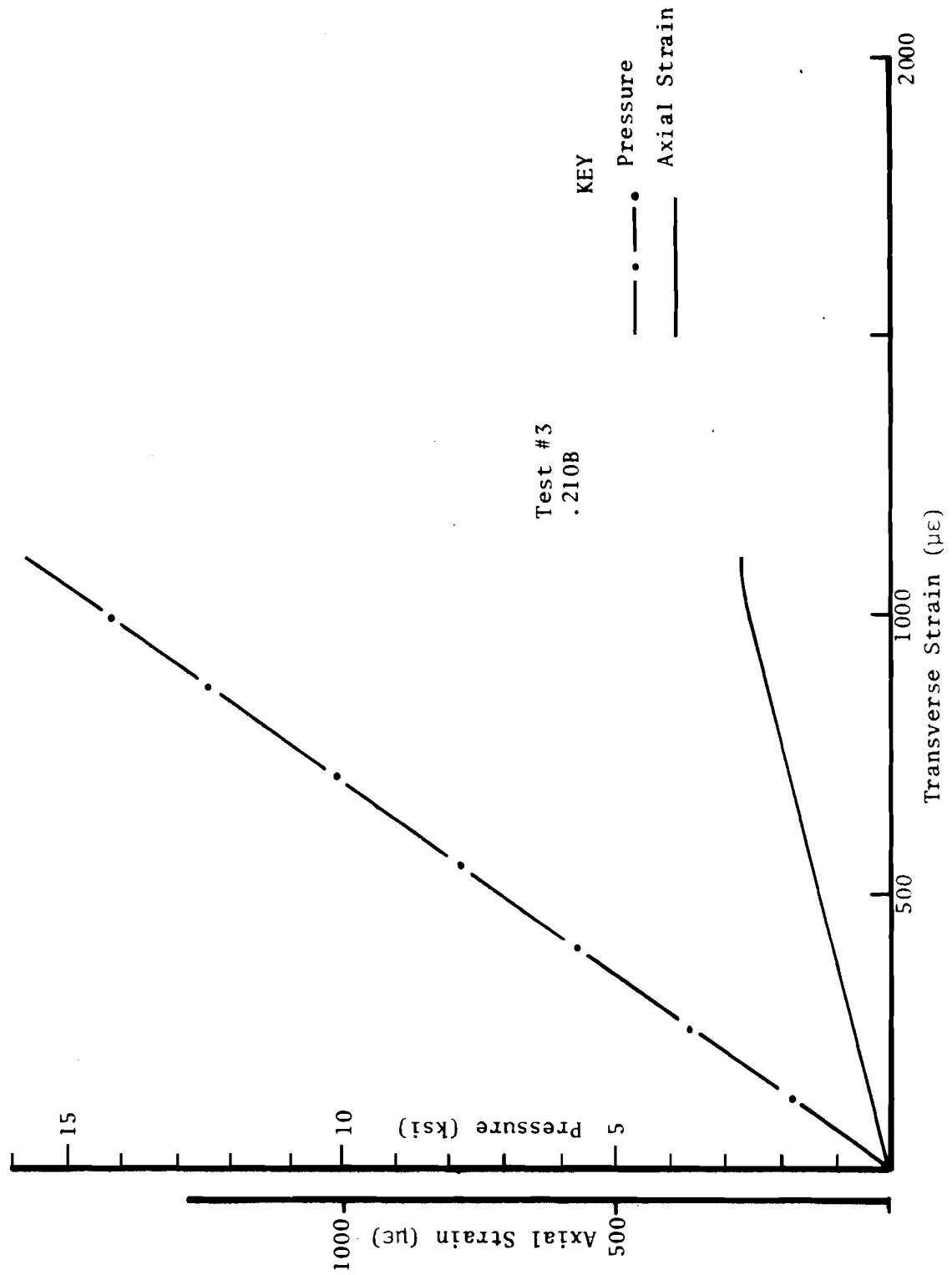
Figure 6. Test #3 Shell Pressure and Axial Strain versus Transverse Strain
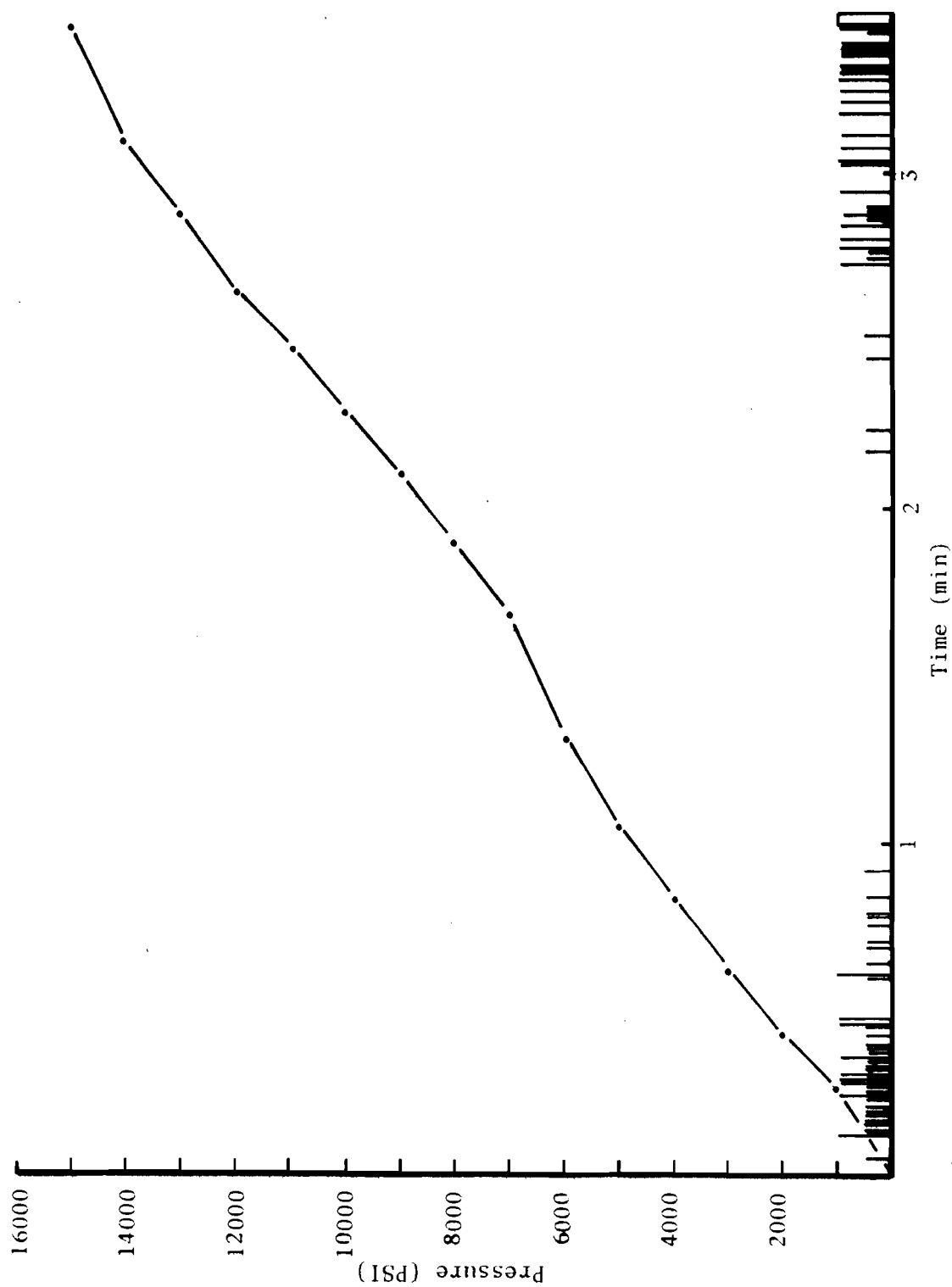
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Figure 7. Test #4 Shell Pressure and Axial Strain versus Transverse Strain

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Figure 8. Test #5 Shell Pressure versus Time with Acoustic Emission Events
(low notch, fatigue crack-yes)

Figure 9. Test #5 Shell Pressure and Axial Strain versus Transverse Strain

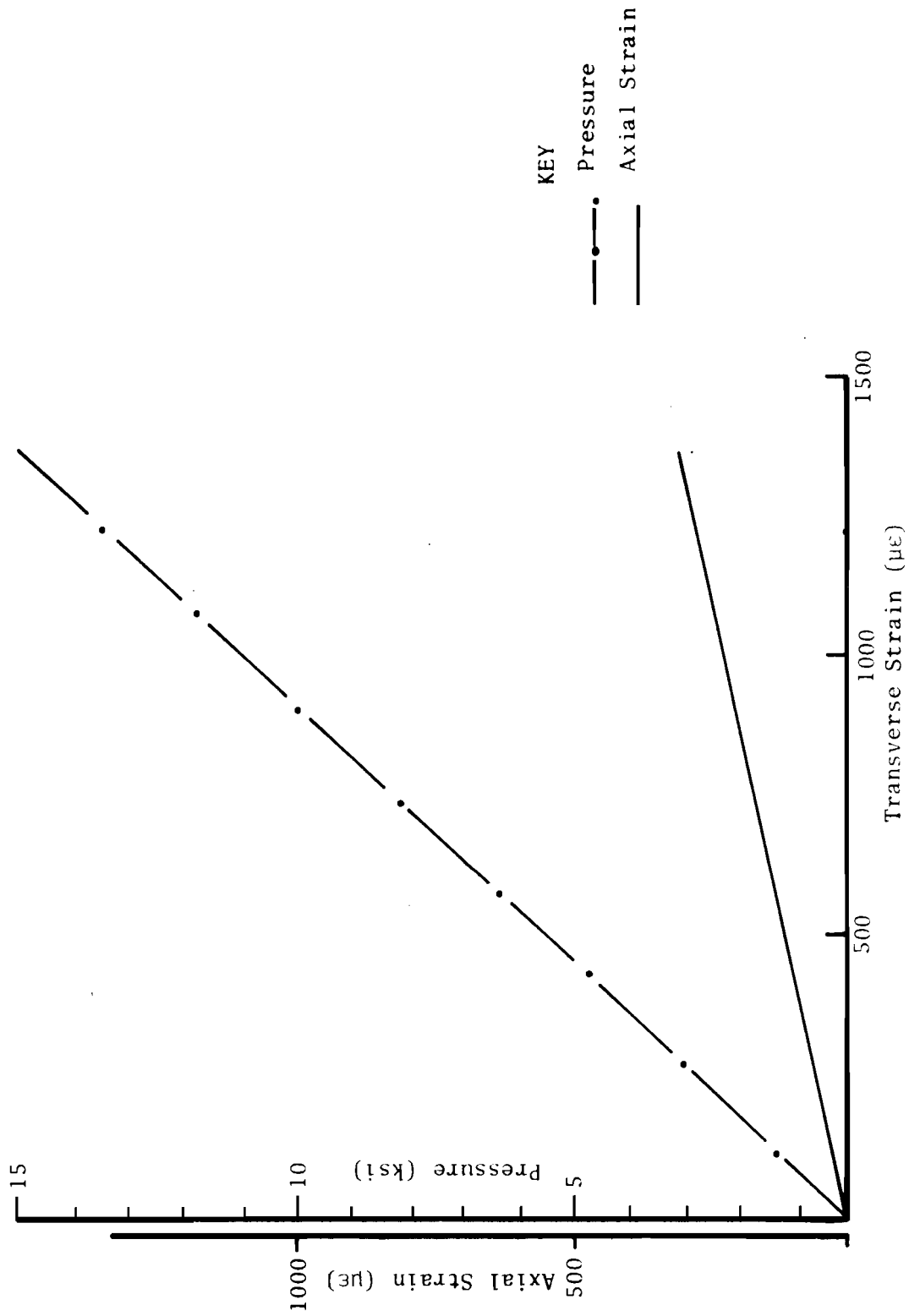Figure 10. Test #6 Shell Pressure versus Time with Acoustic Emission Events (low notch, fatigue crack-yes)

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Figure 11. Test #6 Shell Pressure and Axial Strain versus Transverse Strain
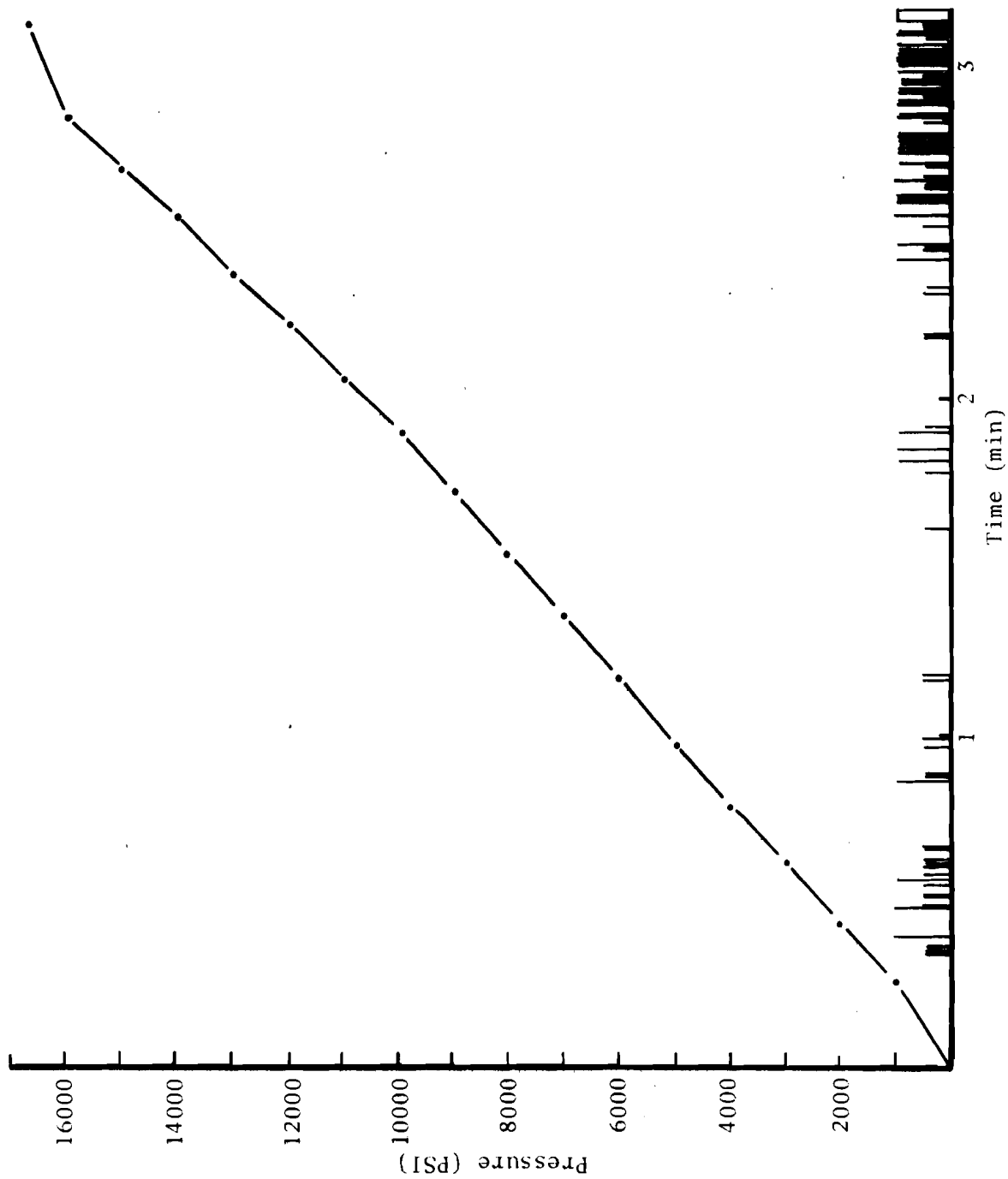
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Figure 12. Test #7 Shell Pressure versus Time with Acoustic Emission Events
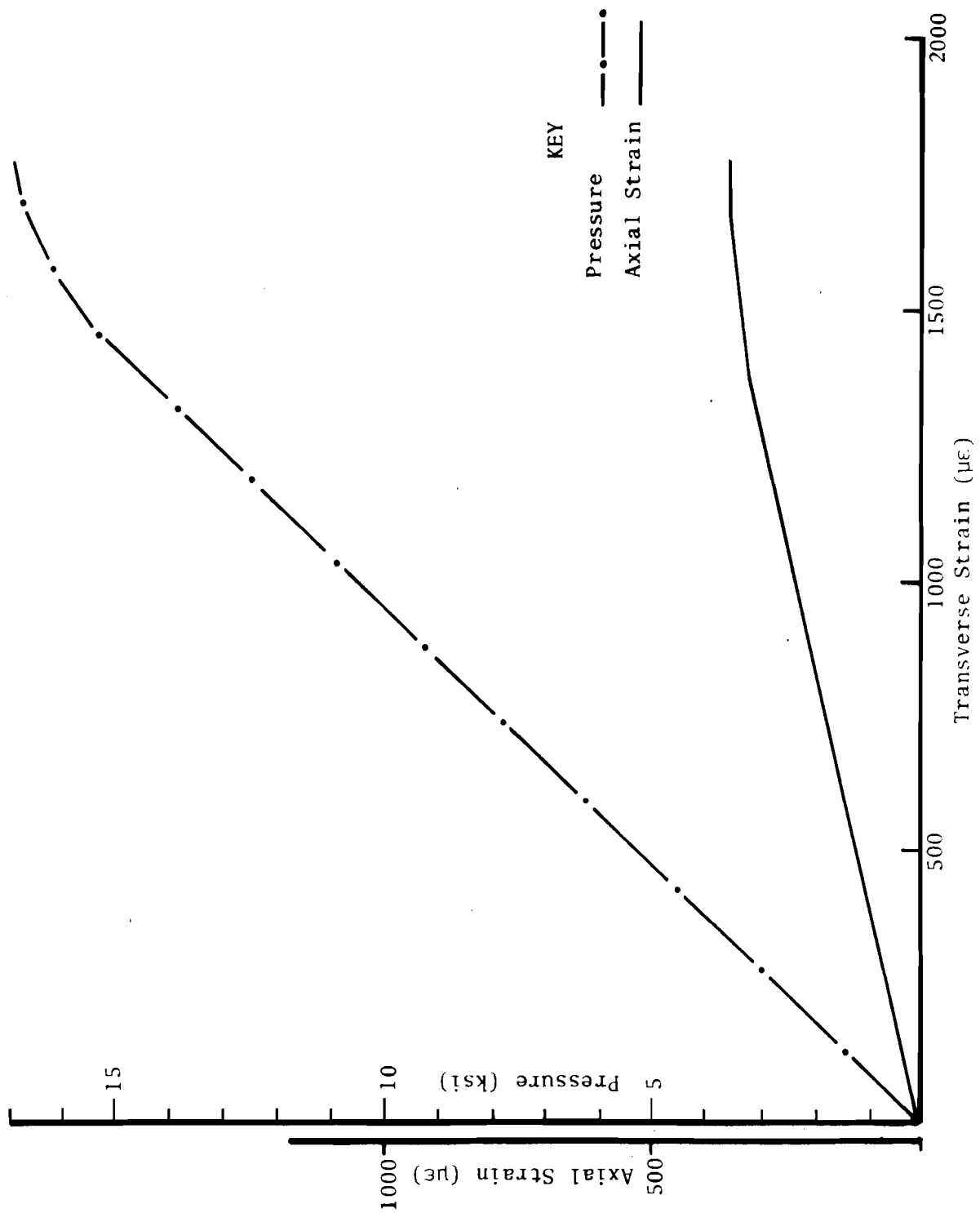(low notch, did not fail)

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Figure 13. Test #7 Shell Pressure and Axial Strain versus Transverse Strain

Figure 14. Test #8 Shell Pressure versus Time with Acoustic Emission Events (low notch, fatigue crack-yes)

31

Figure 15.   Test #8 Shell Pressure and Axial Strain versus Transverse Strain

Figure 16. Test #9 Shell Pressure versus Time with Acoustic Emission Events (high notch, fatigue crack-yes)

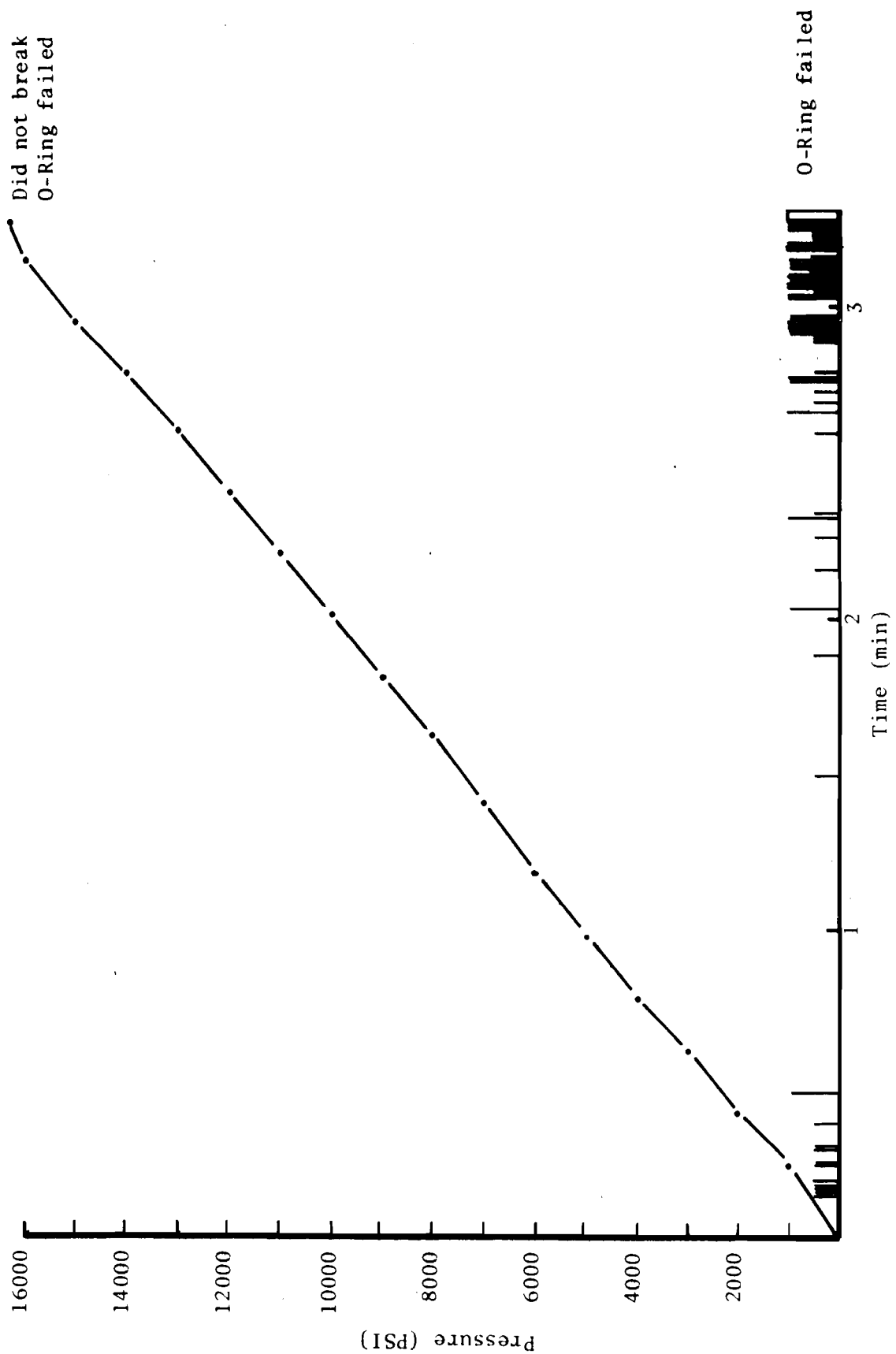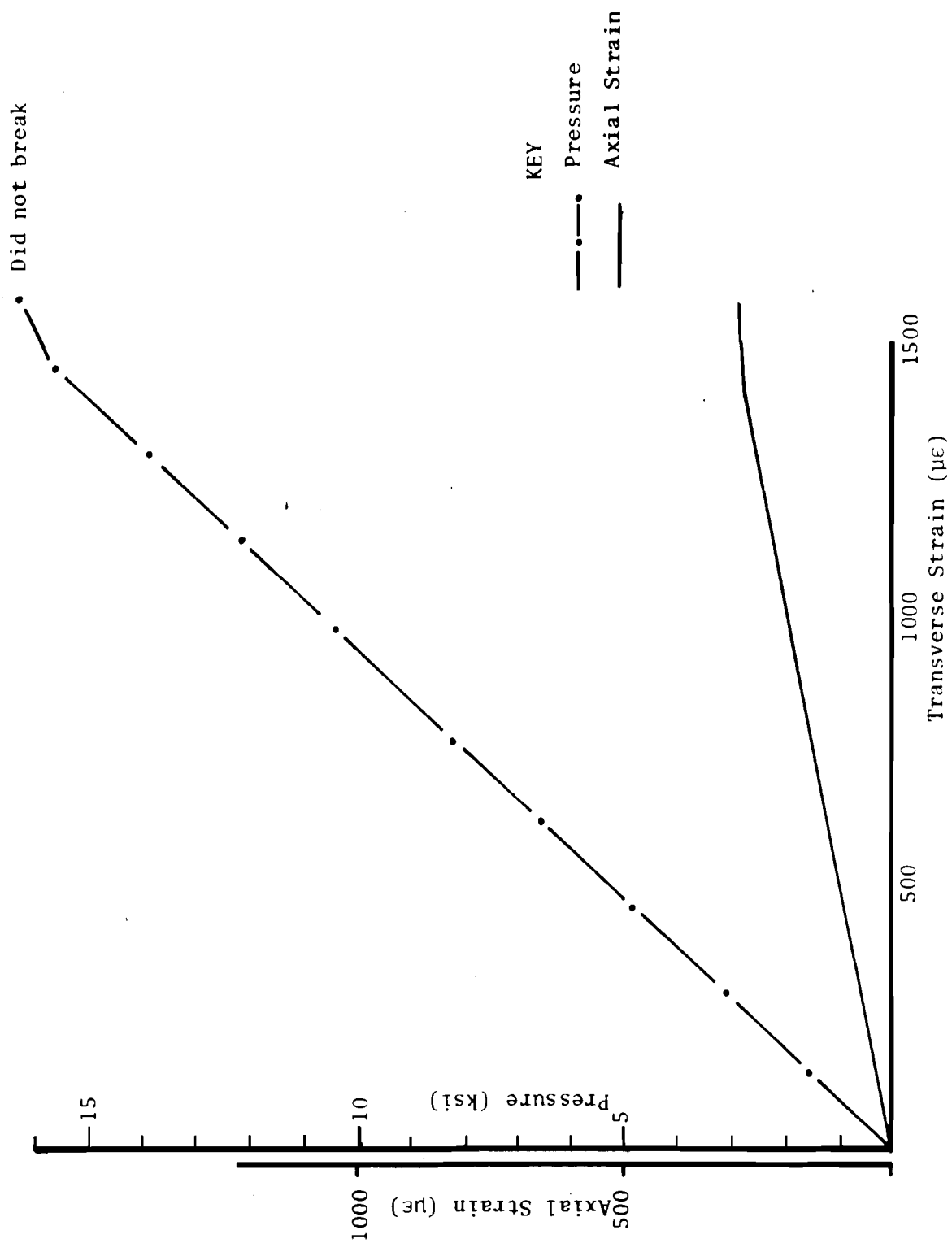Figure 17. Test #9 Shell Pressure and Axial Strain versus Transverse Strain

Figure 18. Test #10 Shell Pressure versus Time with Acoustic Emission Events (high notch, fatigue crack-yes)

Figure 19. Test #10 Shell Pressure and Axial Strain versus Transverse Strain

Figure 20. Test #11 Shell Pressure versus Time with Acoustic Emission Events (high notch, fatigue crack-yes)

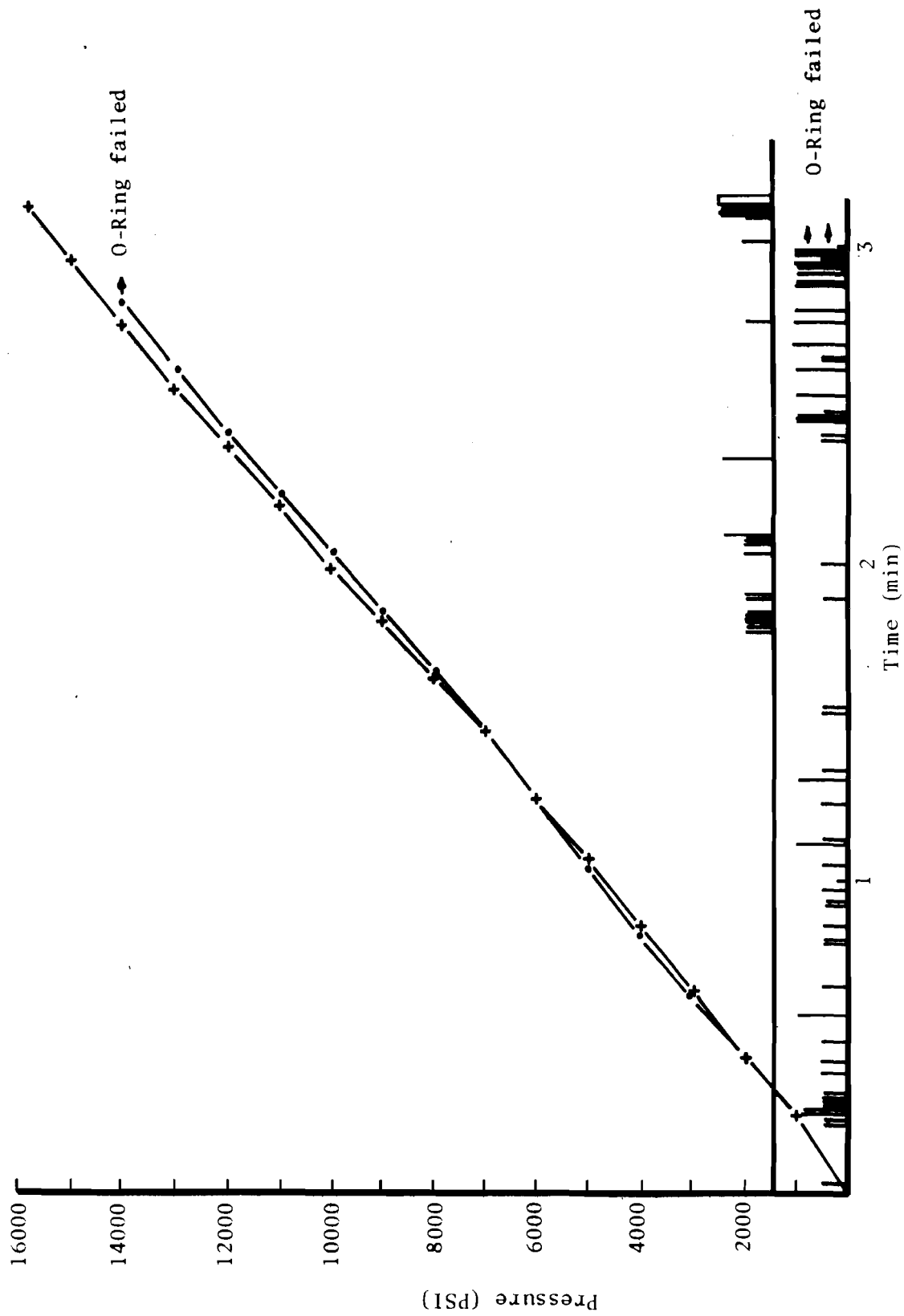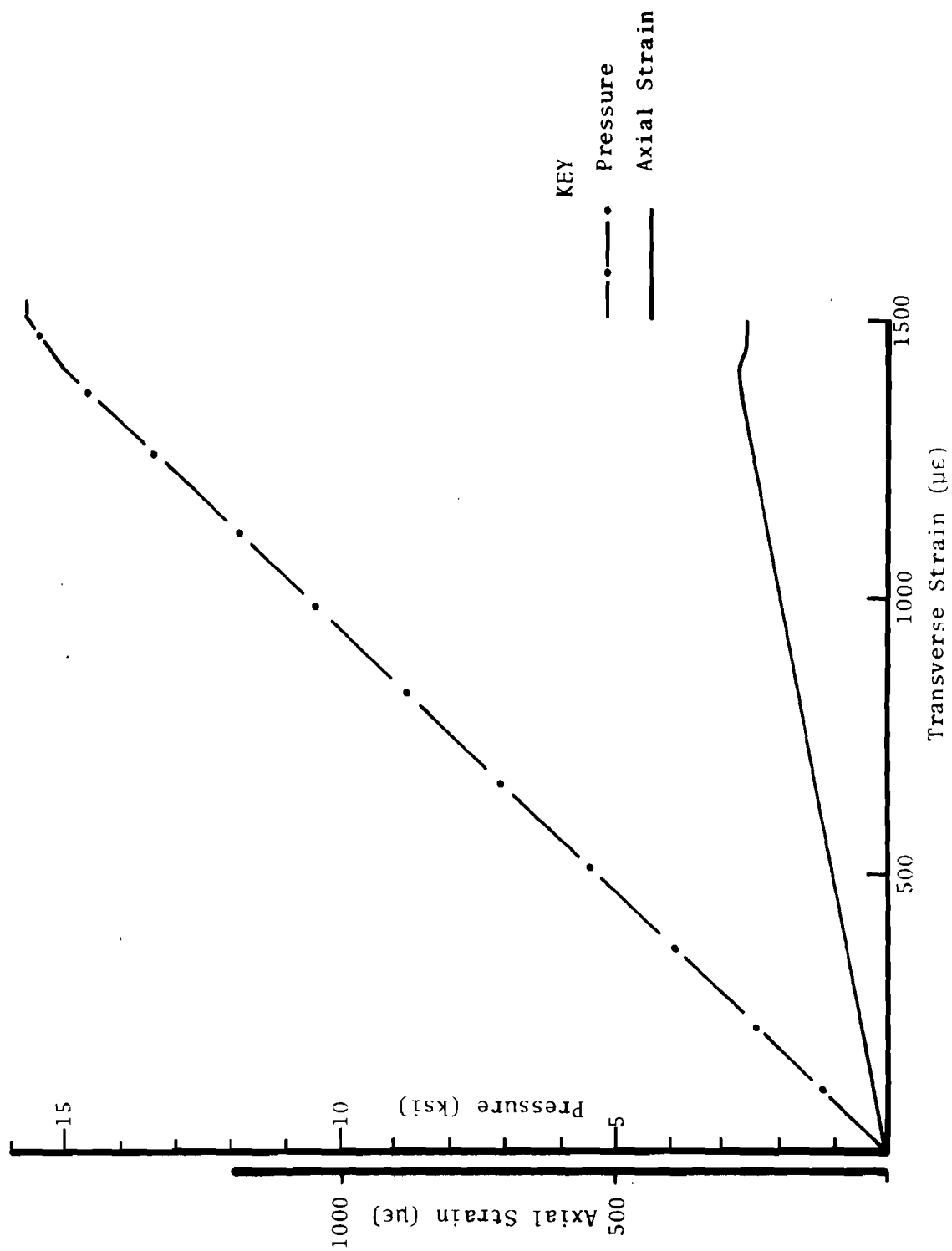Figure 21. Test #11 Shell Pressure and Axial Strain versus Transverse Strain

Figure 22. Test #12 Shell Pressure versus Time with Acoustic Emission Events (high notch, fatigue crack-yes)

Figure 23. Test #12 Shell Pressure and Axial Strain versus Transverse Strain

Figure 24. Test #13 Shell Pressure versus Time with Acoustic Emission Events (high notch, did not fail)

Figure 25. Test #13 Shell Pressure and Axial Strain versus Transverse Strain

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Figure 26. Test #14 Shell Pressure versus Time with Acoustic Emission Events (high notch, didn't fail at notch)

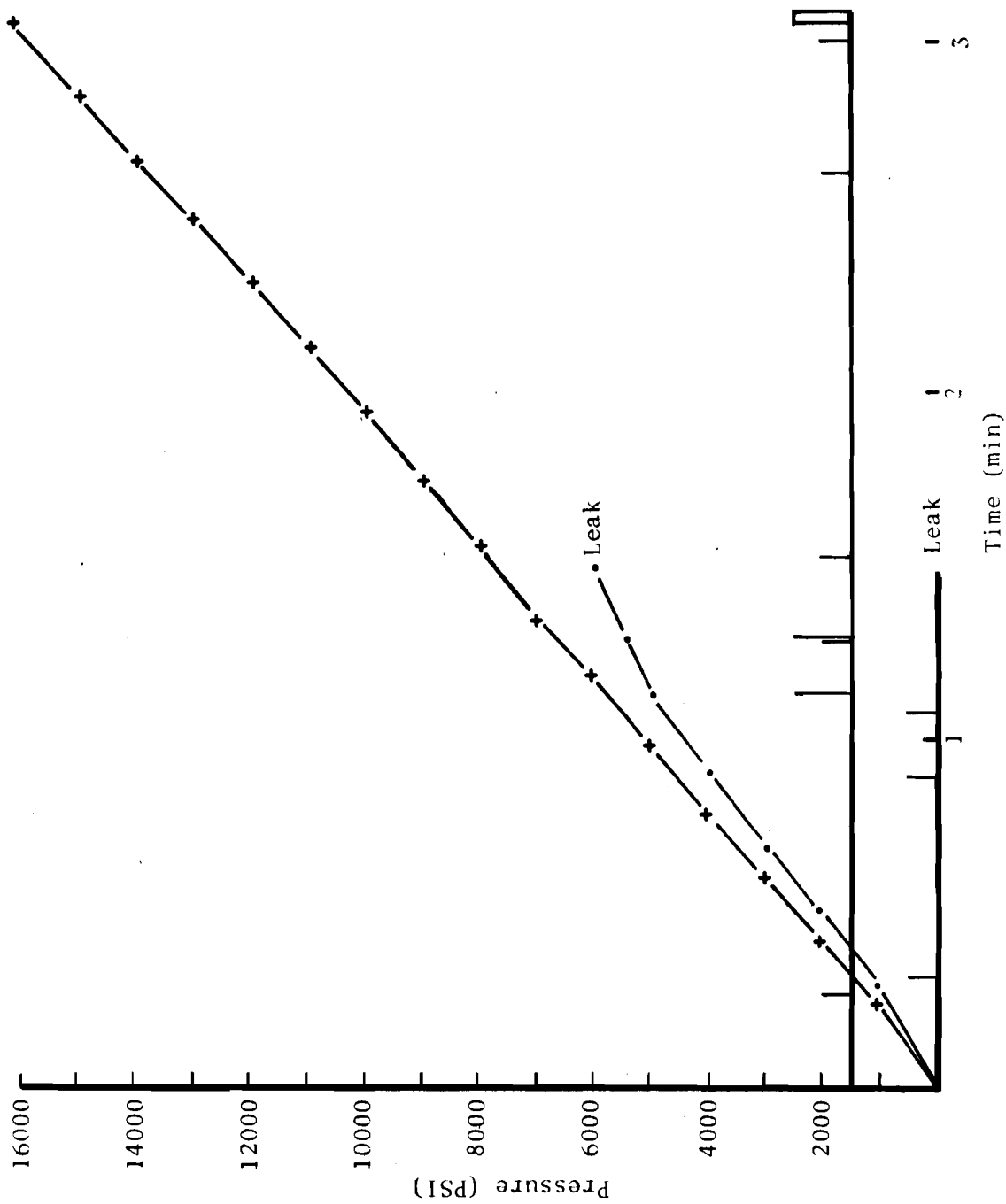Figure 27. Test #14 Shell Pressure and Axial Strain versus Transverse Strain

Figure 28. Test #15 Shell Pressure versus Time with Acoustic Emission Events
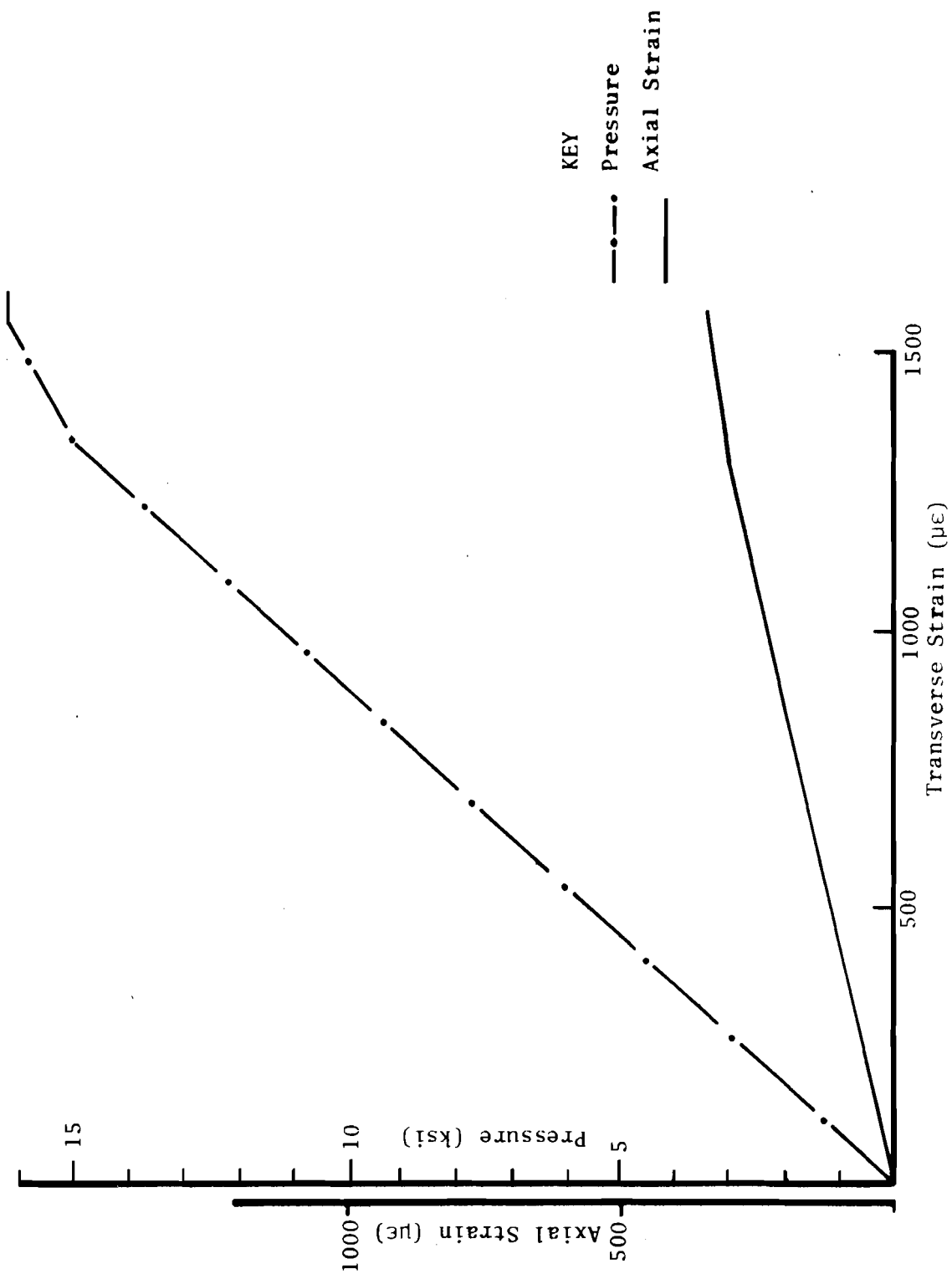(high notch, didn't fail at notch)

45

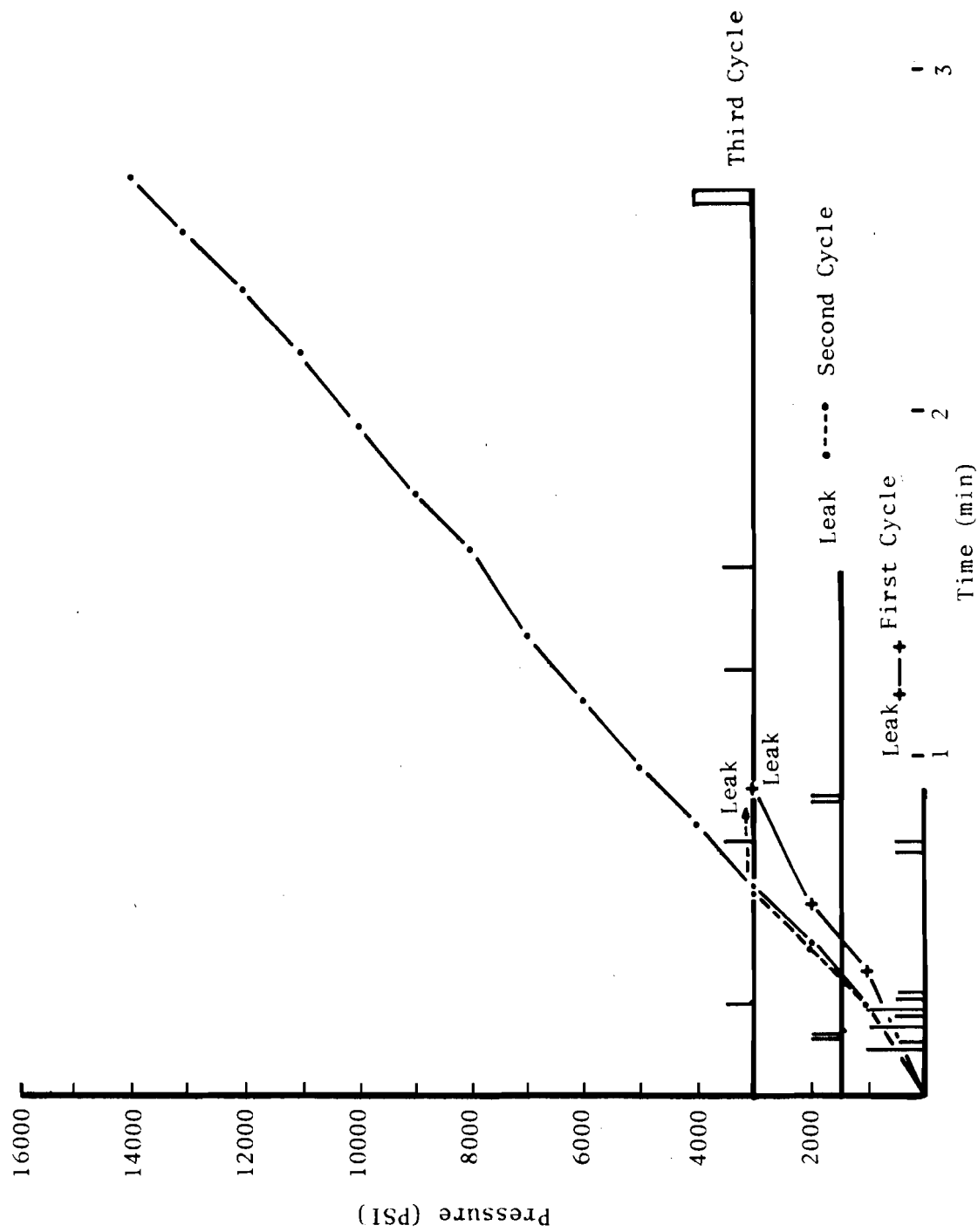Figure 29. Test #15 Shell Pressure and Axial Strain versus Transverse Strain

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Figure 30. Test #16 Shell Pressure versus Time with Acoustic Emission Events (high notch, didn't fail at notch)
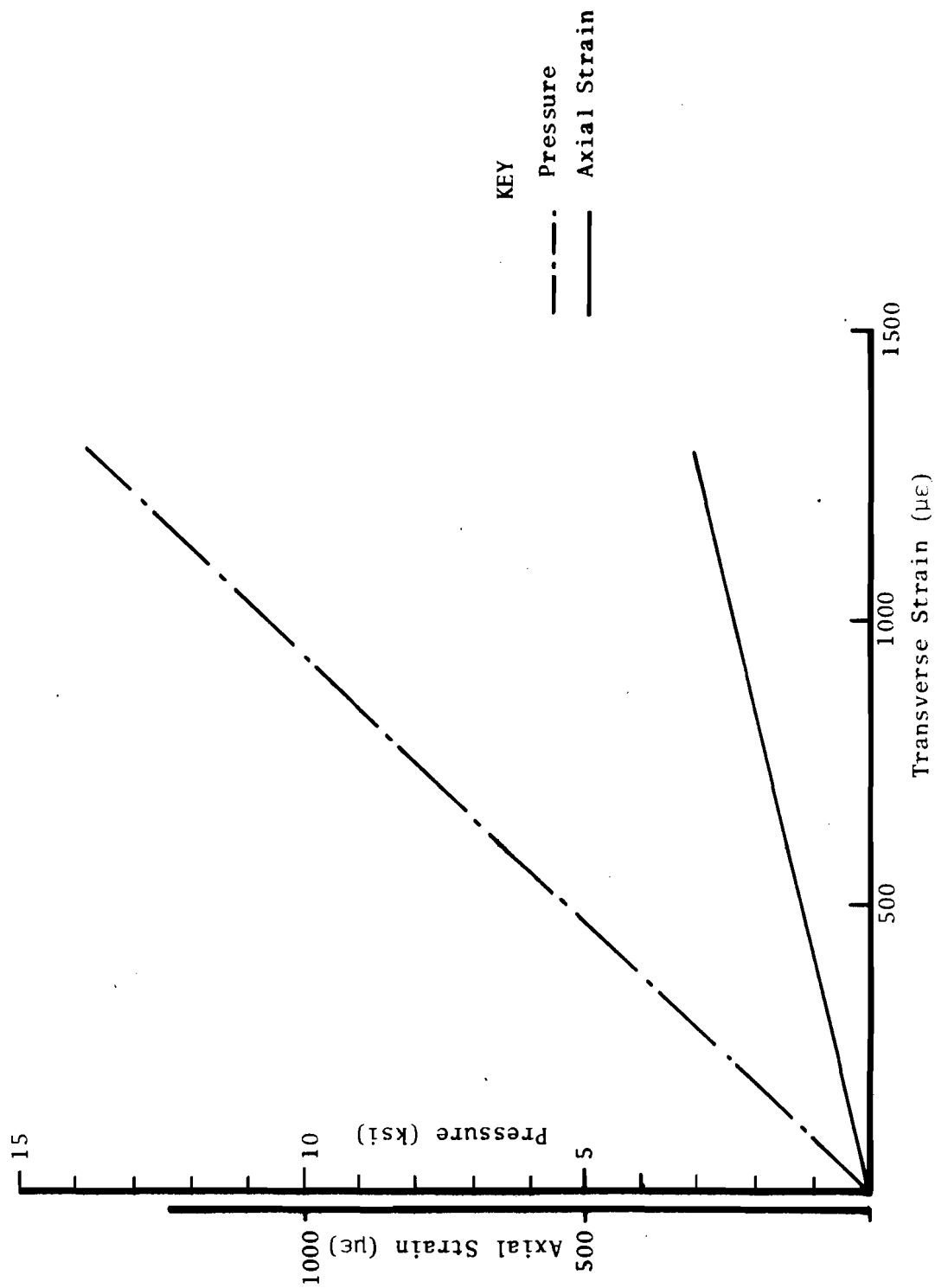
47

Figure 31. Test #16 Shell Pressure and Axial Strain versus Transverse Strain

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Figure 32. Test #17 Shell Pressure versus Time with Acoustic Emission Events (high notch, didn't fail at notch)

49

Figure 33. Test #17 Shell Pressure and Axial Strain versus Transverse Strain

Figure 34. Test #18 Shell Pressure versus Time with Acoustic Emission Events
(high notch, didn't fail at notch)

Figure 35. Test #18 Shell Pressure and Axial Strain versus Transverse Strain
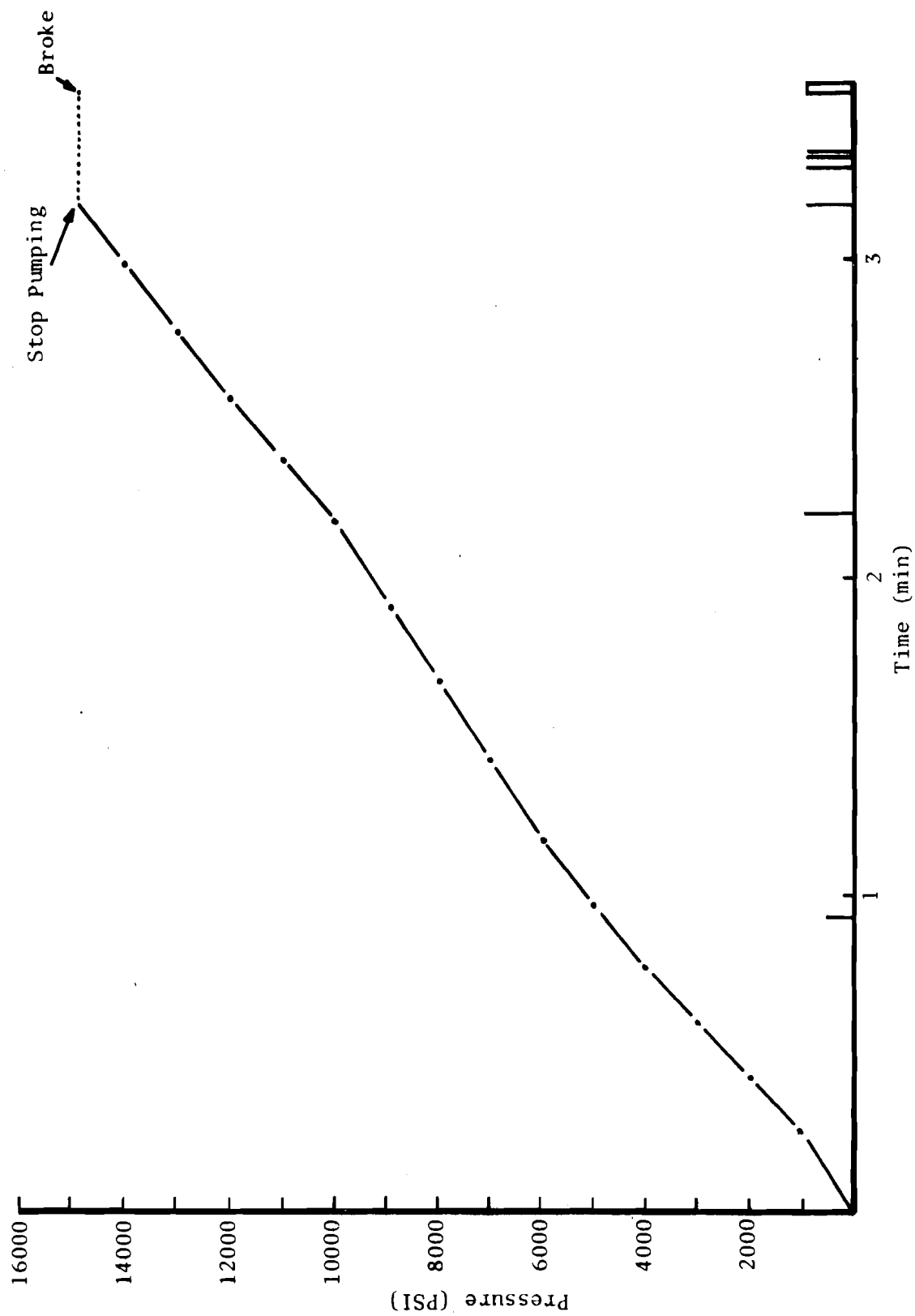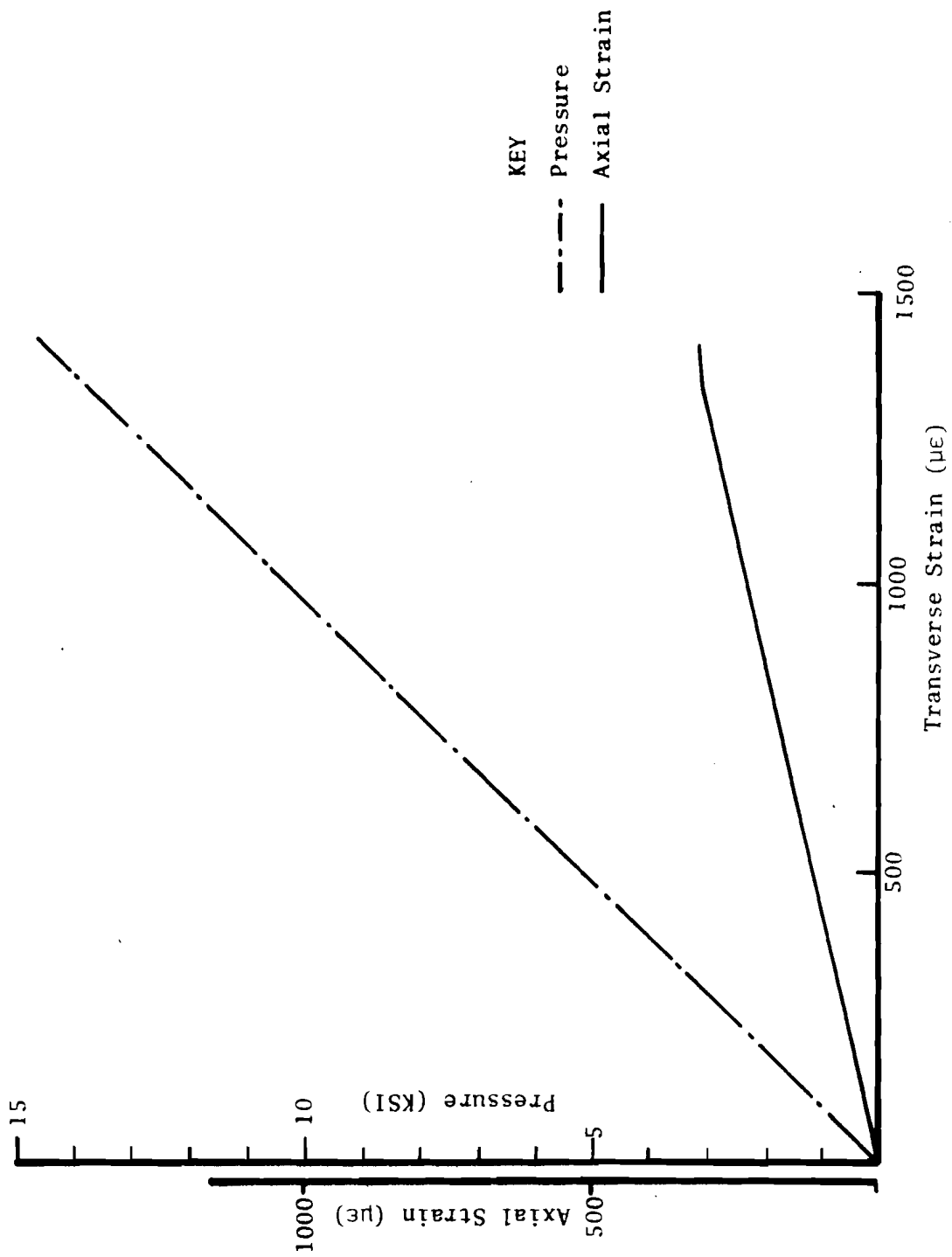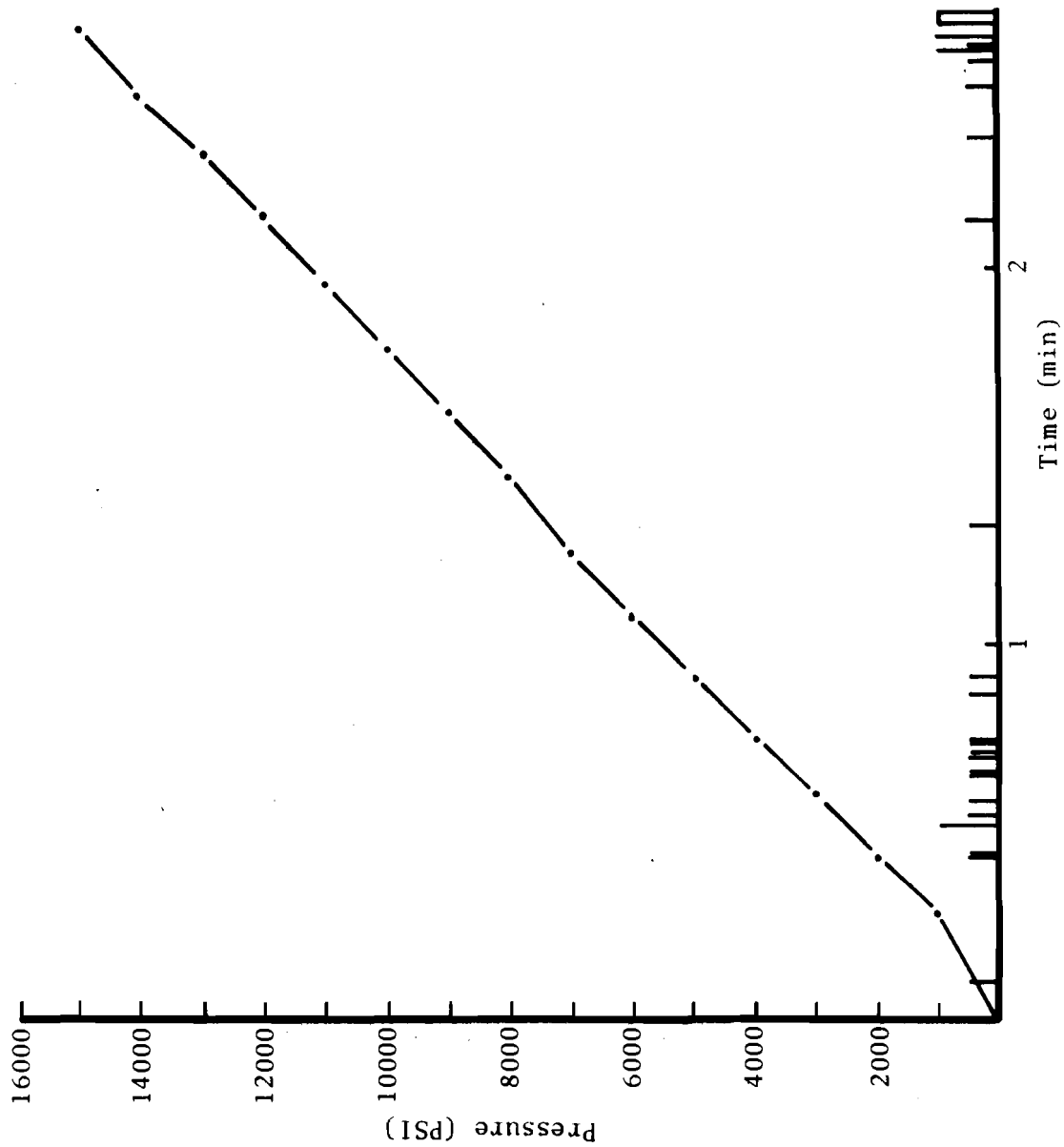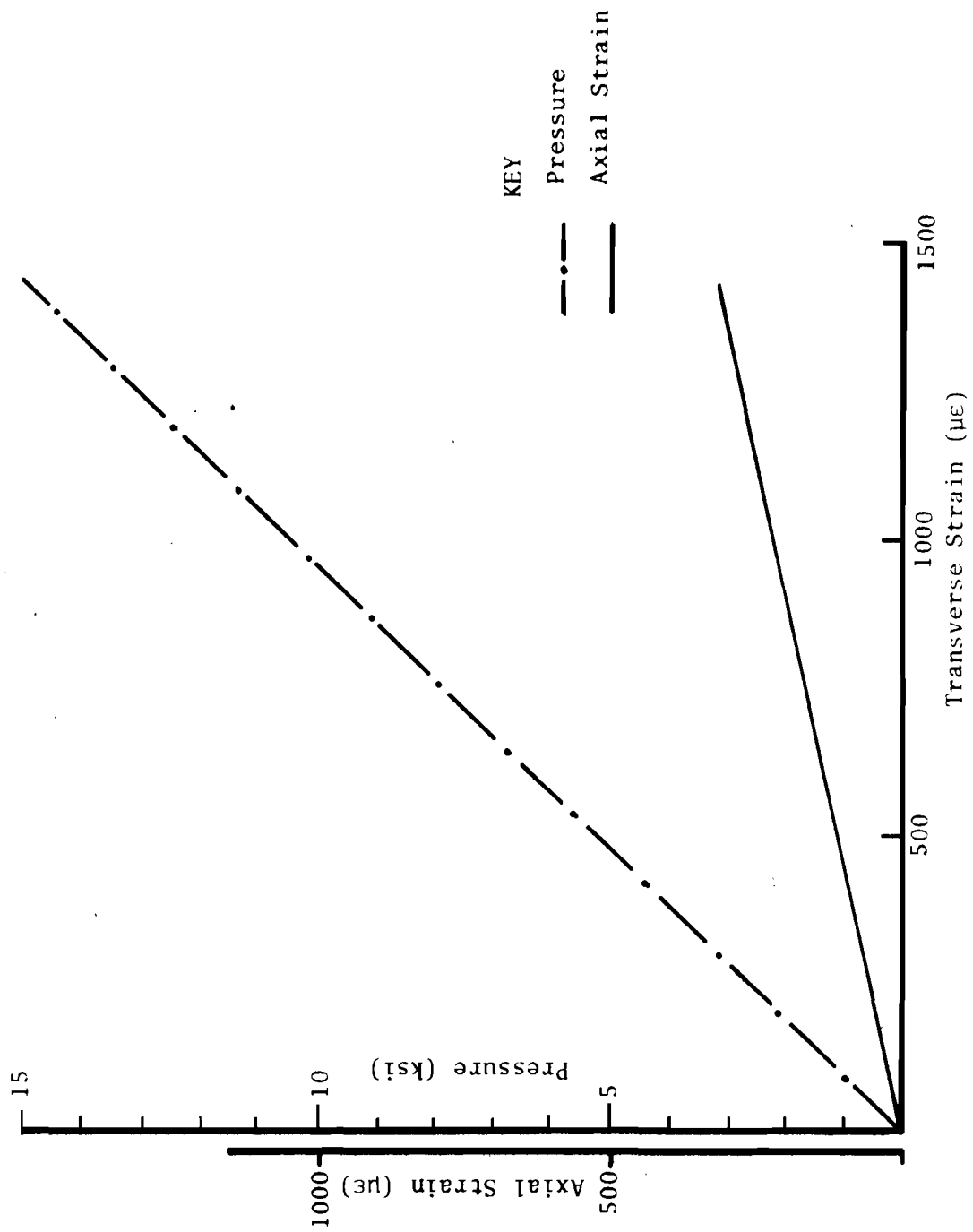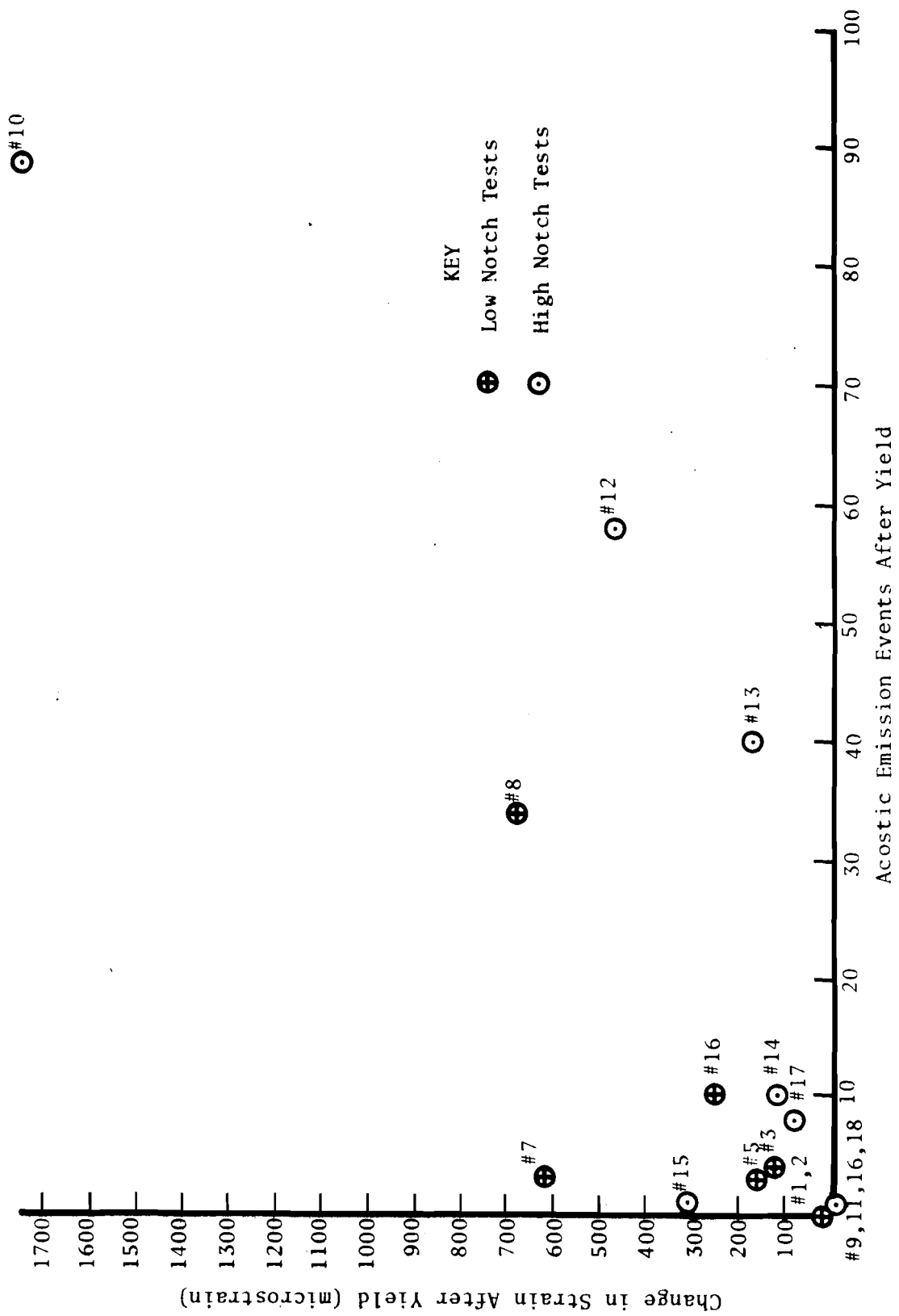
Figure 36. Shell Plasticity After Yield versus Acoustic Emission Events After Yield
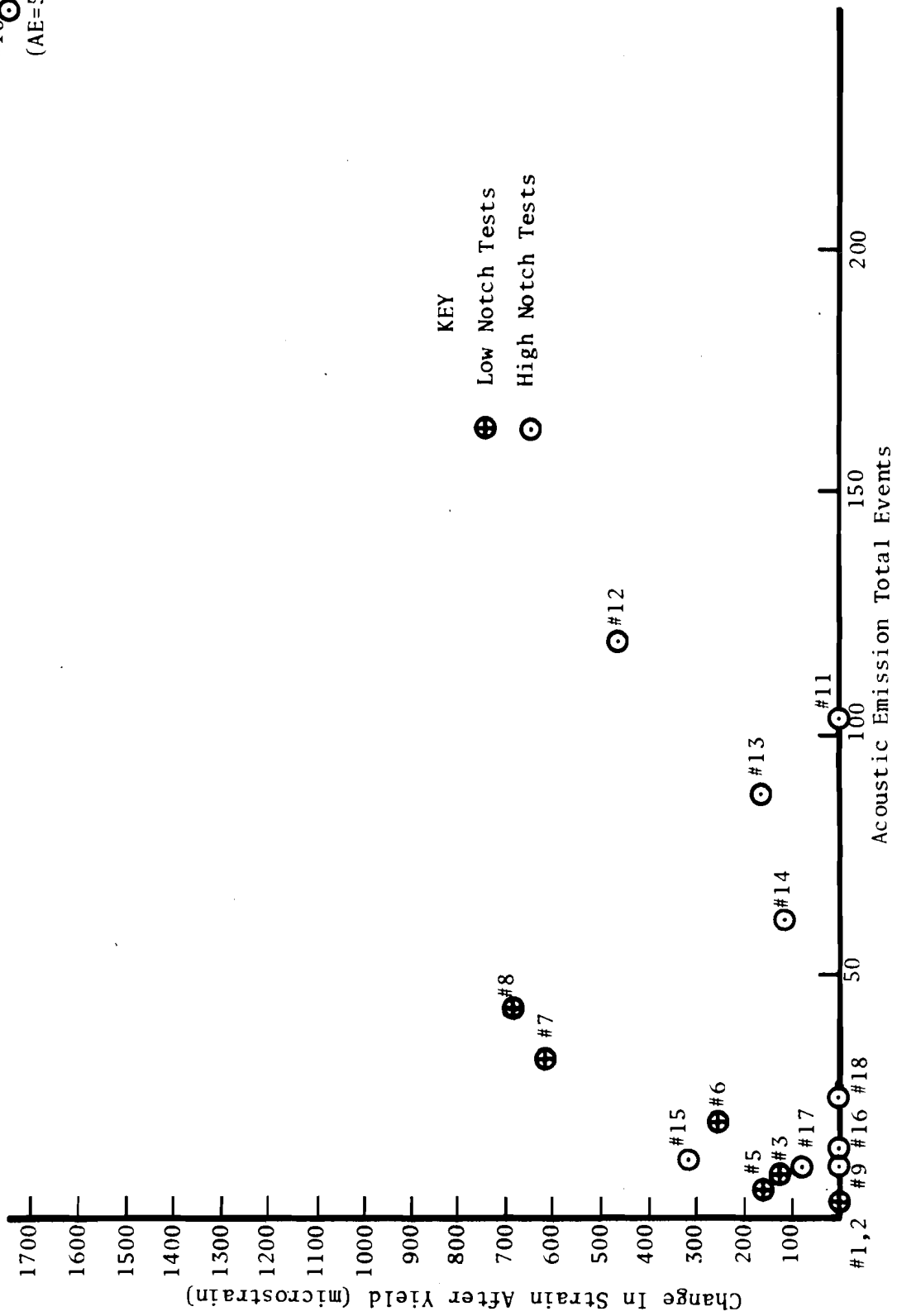
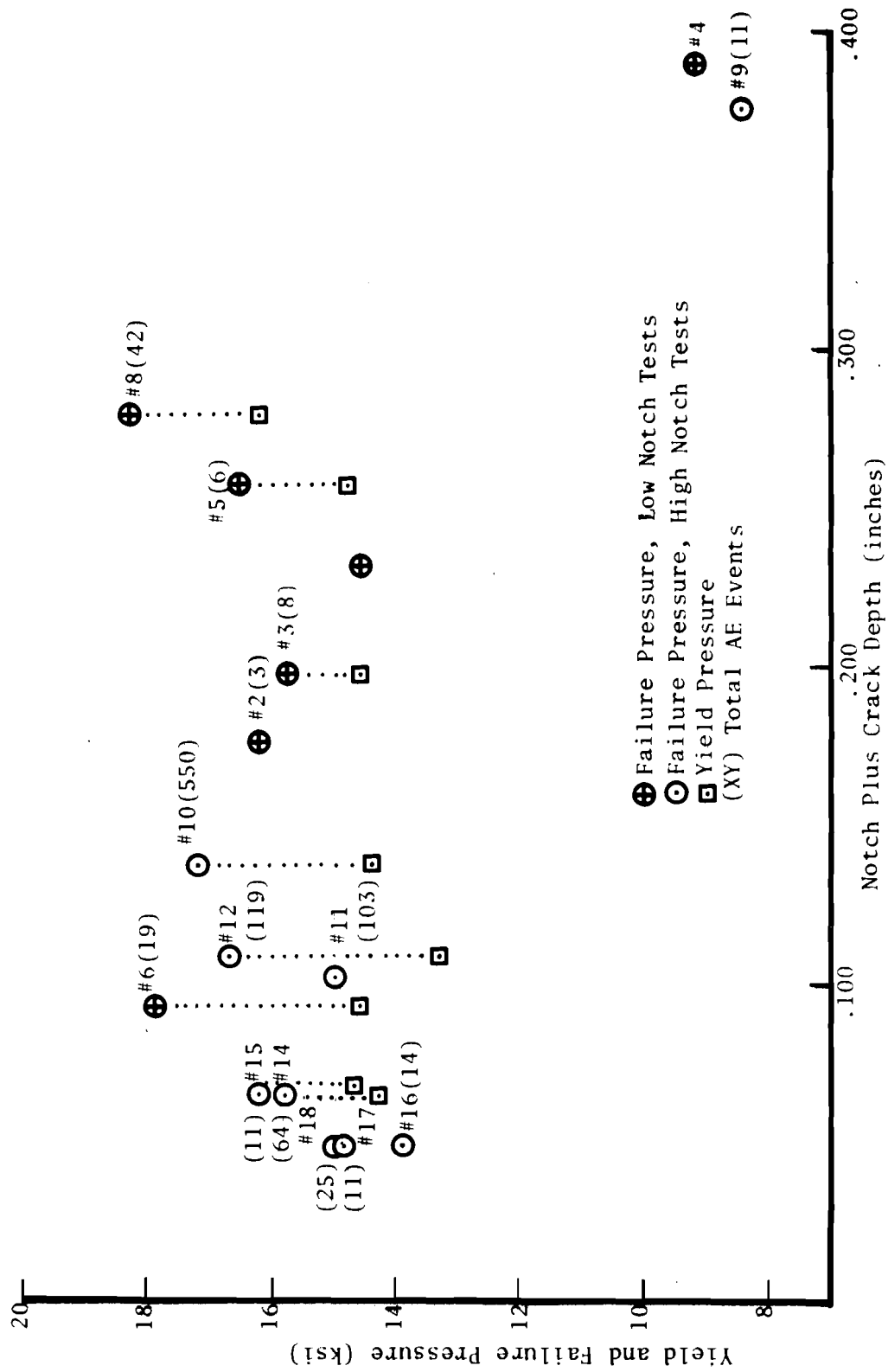Figure 37. Shell Plasticity After Yield versus Total Acoustic Emission Events

Figure 38. Shell Yield and Failure Pressure versus Notch plus Crack Depth

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